UCRL-MI-231287

IFE Science and Technology Strategic Planning Workshop - Part 2: April 25, 2007 Presentations

To select an individual presentation, click the table of contents entry on the next page or click the title on the agenda for Day 2 (using the Hand Tool icon).

To save only a portion of this document, go to File/Print, select Adobe PDF as your printer, specify the desired range of pages, and save to a new file name.

Portions of this work performed under the auspices of the U. S. Department of Energy by University of California Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Part 2 Contents

Technical Program

Day 1, Tuesday, April 24

Overviews - Approaches to IFE

7:00-8:00 Registration and Continental Breakfast

All Day Plenary Session

8:00-8:30 Workshop Motivation and Objectives (Ed Synakowski, LLNL)
8:30-9:00 Setting the Stage for IFE and Workshop Overview (Wayne Meier, LLNL)

Following speakers to address current status, near-term plans, long-range visions and funding needs to move to the next step for the particular approach. With respect to planning, address

- How do you see your approach evolving beyond the near term?
- What needs to be accomplished to move forward on such a strategy?
- What are the potential landscape-changing developments?
- What are the technical issues for your approach?

9:00-9:30 HAPL/KrF (John Sethian, NRL)
9:30-9:40 Q&A

9:40-10:00 Break

10:00-10:30 DPSSL (Al Erlandson, LLNL)
10:30-11:00 Discussion

11:00-11:30 FTF (Steve Obenschain, NRL)
11:30-12:00 Discussion

12:00-1:00 Lunch

1:00-1:30 HIF (Grant Logan, LBNL)
1:30-2:00 Discussion

2:00-2:30 Z-IFE (Craig Olson, SNL)
2:30-3:00 Discussion

3:00-3:15 Break

3:15-3:45 FI as a Cross-Cutting Option for IFE (Mike Campbell, GA)
3:45-4:00 Discussion

4:00-4:30 The Potential Benefits of Magnetic Fields in Inertially Confined Plasmas (Bruno Bauer, UNR)
4:30-4:45 Discussion

4:45-6:00 Panel Discussion (M. Campbell, S. Dean, G. Logan, C. Olson, C. Sangster, J. Sethian, E. Synakowski)
What can/should we do to be prepared to take advantage of growing interest in and funding for IFE that could be triggered by a variety of events (e.g., successful ignition on NIF, increase concern about global climate change, increase interest in domestic energy sources, etc.)?

Day 2, Wednesday, April 25

Working Together in the Near-Term to Advance IFE and Related Science

7:30-8:00 Continental Breakfast

Interagency Approach to High Energy Density Laboratory Plasmas (HEDLP)
8:00-8:20 Overview of the National Task Force Report on HEDP: Setting the Stage (Ron Davidson, PPPL)
8:20-8:50 OFES, NNSA Perspectives (Ray Fonck, OFES; and Chris Keane, NNSA)
8:50-9:15 Updated Planning for HED-LP (Francis Thio, OFES)
9:15-9:45 Discussions

9:45-10:00 Break

Plenary Talks: Existing and near-term ICF/HEDP capabilities and research plans focusing on R&D relevant to IFE
Questions to focus the plenary talks include:

- What are the HEDP questions that can be addressed in the near-term that are relevant to IFE? How can NNSA facilities be used to support IFE both now and post ignition?
- What are current or planned interactions with the other communities (ICF/HEDP/IFE)?
- Who are the customers for this HEDP science besides the IFE/ICF community?

ICF/HEDP Facilities and R&D:
10:00-10:45 NIC and NIF (John Lindl, LLNL)
10:45-11:15 Omega (John Soures, UR-LLE)
11:15-11:45 Z-pinch (Keith Matzen, SNL)
11:45-12:15 Nike--1) ICF Experiments and Plans, 2) ICF Physics Issues (Andy Schmitt, NRL)

12:15-1:15 Lunch

1:15-1:45 Advanced Ignition (Fast and other two-step ignition) (Riccardo Betti, UR-LLE)
1:45-2:15 HIFS/WDM/Hydrodynamics Experiments on NDCX-I and NDCX-II (John Barnard, LLNL)
2:15-2:45 A Pathway to HEDP: Magnetized Target Fusion (Glen Wurden, LANL)

2:45-3:00 Break

3:00-5:00 PM - Breakout Session - Working Together to Advance IFE and Related Science*
Four groups. Same questions for each group:

- What are the HEDP questions that can be addressed in IFE-relevant NNSA and OFES facilities? Which questions are directly relevant to IFE? What types of IFE relevant experiments can be done on NNSA ICF facilities?
- How does addressing these questions enable progress in IFE?
- What opportunities exist that can be captured with growing budgets?
- How are the IFE/ICF/HEDP communities working together to maximize use of limited resources to advance the underlying science of IFE? What obstacles exist? How can these working relationships be improved?

***Breakout group leaders to prepare a single summary talk to be given the final day.**

Day 3, Thursday, April 26

International Perspective and IFE Science and Technology in the Long Term

7:30-8:00 Continental Breakfast

International Activities
8:00-8:30 FIREX Project (Hiroshi Azechi, ILE, Osaka, Japan)
8:30-9:00 HiPER and other EU Activities (Mike Dunne, UK)
9:00-9:30 IAEA Coordinated Research Program on IFE (Neil Alexander, GA)

9:30-10:00 Discussion on opportunities for international collaborations

10:00-10:15 Break

10:15 AM-12:00 PM – Contributed/Solicited talks (~ 5 @ 15-20 min each)
Other (non-driver) Enabling and Cross-Cutting Science and Technology

- A Survey of Advanced Target Options for IFE (John Perkins, LLNL)
- Ion-Driven Fast Ignition: Scientific Challenges and Tradeoffs (Juan Fernandez, LANL)
- Thick Liquid Protection for Inertial Fusion Energy Chambers (Per Peterson, UCB)
- Dry Wall Chamber Designs (Rene Raffray, UCSD)
- Status of Developing Target Supply Methodologies for Inertial Fusion (Dan Goodin, GA)

12:00-1:00 PM - Lunch

1:00-3:00 Poster Session (contributed posters)

3:00-5:00 PM - Breakout Session - IFE Planning*
Four groups. Same questions for each group:

- What are the elements of a compelling breakout strategy for IFE?
- What advances have to be made to make such a strategy credible?
- What advances can only be made with increased funding?
- Have views of an IFE development path changed since FESAC report? If so, how?

***Breakout group leaders to prepare a single summary talk to be given the final day.**

Day 4, Friday, April 27

Next Generation and Next Steps

8:00-8:30 Continental Breakfast

8:30-10:00 AM - Panel Discussion
Training the Next Generation: University Participation in HEDP and IFE Science and Technology
(5 minute introductions + Discussion)
(Bruno Bauer, UNR; Farhat Beg, UCSD; Linn Van Woerkom, OSU; Shahram Sharafat, UCLA; Brian Wirth, UCB)

10:00-10:15 Break

Summaries from Breakout sessions
(up to 30 minute presentation plus 15 minute discussion)

10:15-11:00 Wednesday Breakout Summary: HEDP Opportunities for IFE (Ed Synakowski, LLNL)
11:00-11:45 Thursday Breakout Summary: IFE Planning (Steve Dean, FPA)

11:45 AM - 12:00 PM - Concluding Remarks, Action Items, Next Steps

12:00 PM - Adjourn

National Task Force Report on High Energy Density Physics - Setting the Stage

Ronald C. Davidson

Plasma Physics Laboratory
Princeton University

Presented at

Strategic Planning Workshop
On IFE Science and Technology

San Ramon, California

April 24 - 27, 2007

Outline of Presentation

There have been two national studies that identify research opportunities of high intellectual value in high energy density plasma science. The studies were commissioned by:

• National Academies - National Research Council (*Frontiers in High Energy Density Physics, - The X-Games of Contemporary Science* National Academies Press, 2003).

• Office of Science and Technology Policy's Interagency Working Group on the Physics of the Universe (National Task Force Report on High Energy Density Physics, July, 2004).

Scope of the National Research Council Study

The committee recognized that it is a highly opportune time for the nation's scientists to develop a fundamental understanding of the physics of high energy density plasmas.

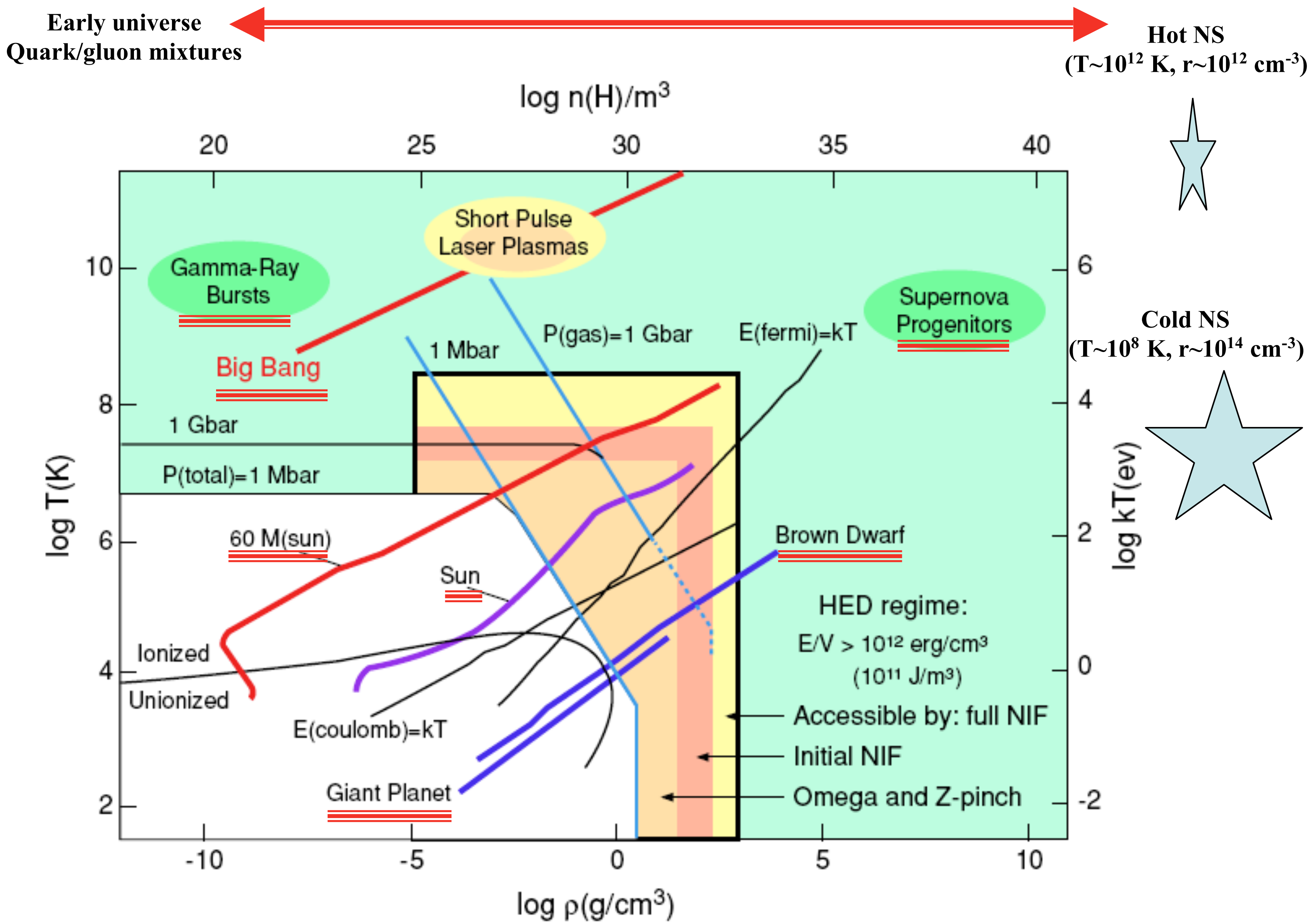
The space-based and ground-based instruments for measuring astrophysical processes under extreme conditions are unprecedented in their accuracy and detail.

In addition, a new generation of sophisticated laboratory systems ('drivers') exists or is planned that create matter under extreme high energy density conditions (exceeding 10^{11} J/m^3), permitting the detailed exploration of physical phenomena under conditions not unlike those in astrophysical systems.

Definition of High Energy Density

- The region of parameter space encompassed by the terminology ‘high energy density’ includes a wide variety of physical phenomena at energy densities exceeding 10^{11}J/m^3.
- In the figure, "High-Energy-Density" conditions lie in the shaded regions, above and to the right of the pressure contour labeled "P(total)=1 Mbar".

MAP OF THE HED UNIVERSE



Attributes of High Energy Density

- High energy density physics (for example, pressure conditions exceeding 1 Mbar) is a rapidly growing field, with exciting research opportunities of high intellectual challenge.

- The field spans a wide range of areas, including plasma physics, laser and particle beam physics, materials science and condensed matter physics, nuclear physics, atomic and molecular physics, fluid dynamics and magnetohydrodynamics, and astrophysics.

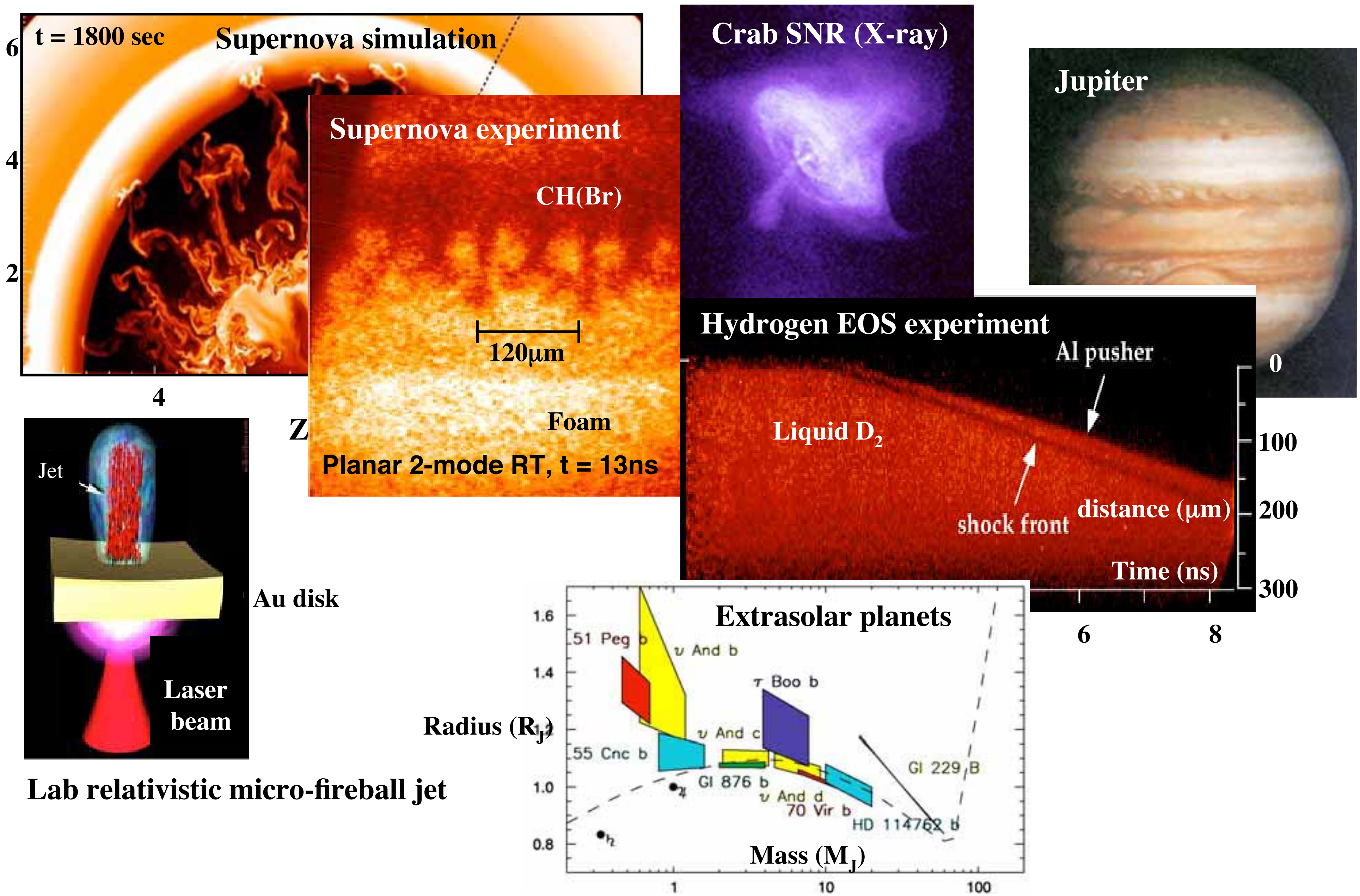
- A new generation of sophisticated laboratory facilities and diagnostic instruments exist or are planned that create and measure properties of matter under extreme high energy density conditions.

- This permits the detailed laboratory exploration of physics phenomena under conditions of considerable interest for basic high energy density physics studies, materials research, understanding astrophysical processes, commercial applications (e.g., EUV lithography), inertial confinement fusion, and nuclear weapons research.

Physical Processes and Areas of Research

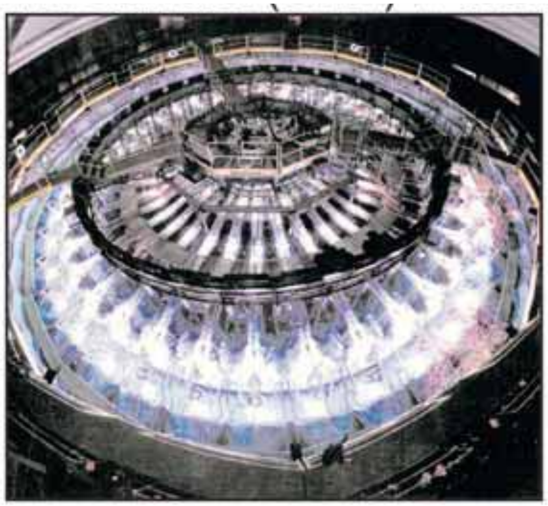
High Energy Density Astrophysics
Beam- Plasma Interactions
Free Electron Laser Interactions
Equation of State Physics
Theory and Advanced Computations
Radiation-Matter Interaction
Laser-Plasma Interactions
Beam-Laser Interactions
High-Current Discharges
Physics of Highly Stripped Atoms
Inertial Confinement Fusion
Hydrodynamics and Shock Physics

High Energy Density Plasma Science and Astrophysics

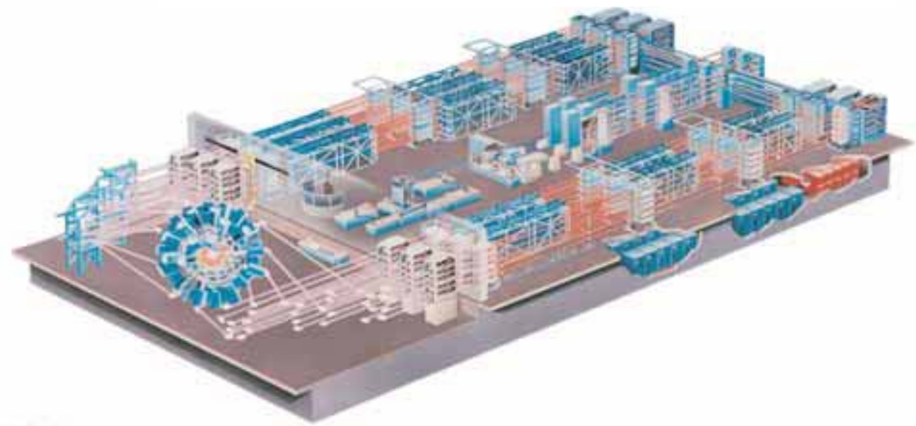


Current and future facilities open new frontiers in experimental high energy density science

20 MA SNLA Z-Facility

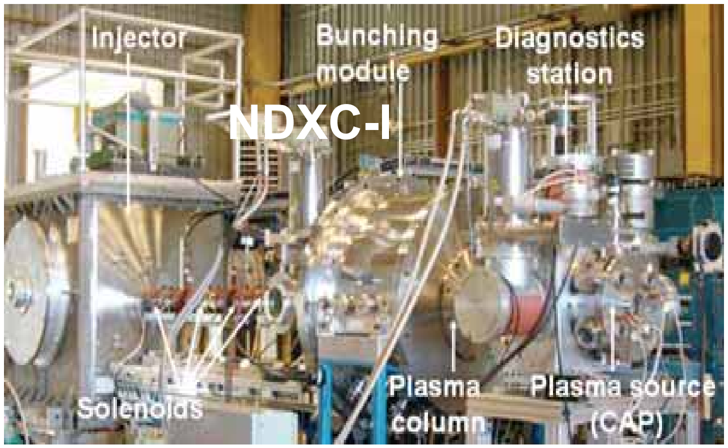


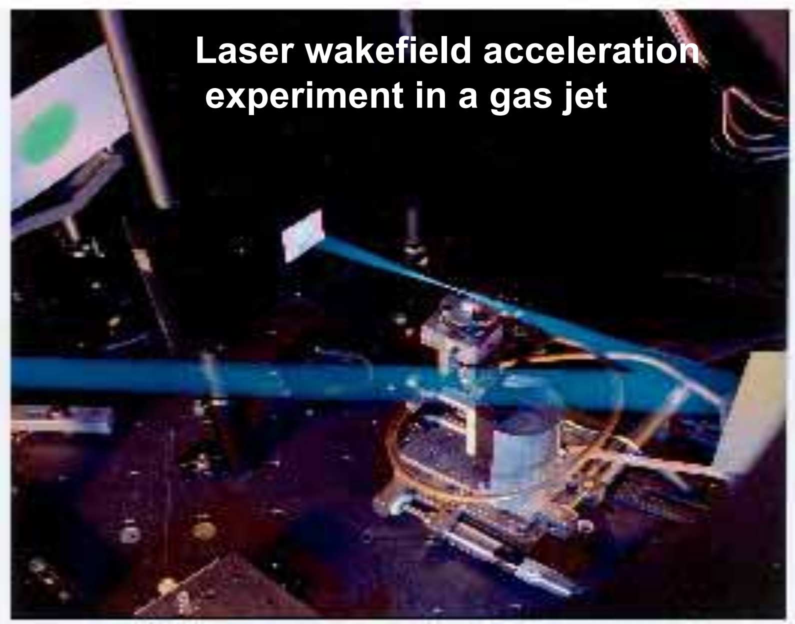
30-kJ OMEGA laser (UR-LLE)



2-MJ National Ignition Facility (NIF) under construction at LLNL

Facilities for Laser-Plasma and Beam-Plasma Interactions Range from Very Large to Tabletop Size





Conclusions of the National Research Council Study

Accomplishments of the study:

- Reviewed advances in high energy density physics on laboratory and astrophysical scales.
- Developed a unifying framework for the field.
- Assessed the field, and highlighted scientific research opportunities.
- Identified intellectual challenges.
- Outlined strategy to extend forefronts of the field.

Illustrative future challenges:

- Clearly identify research thrusts and compelling questions of high intellectual value.
- Foster federal support for high energy density physics by multiple agencies.

TASK FORCE CHARGE AND APPROACH

In response to the January 13, 2004, charge letter from Joe Dehmer on behalf of the Interagency Working Group, the HEDP Task Force addressed the following key charge areas in order to identify the major components of a national high energy density physics program:

1. Identify the principal research thrust areas of high intellectual value that define the field of high energy density physics;

2. For each of the thrust areas, identify the primary scientific questions of high intellectual value that motivate the research;

TASK FORCE CHARGE AND APPROACH

3. Develop the compelling scientific objectives and milestones that describe what the federal investment in high energy density physics are expected to accomplish;

4. For each principal thrust area, identify the frontier research facilities and infrastructure required to make effective progress; and

5. Identify opportunities for interagency coordination in high energy density physics.

KEY BACKGROUND REFERENCES FOR TASK FORCE DELIBERATIONS

HEDP Task Force

1. *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century* (National Academies Press, 2003);

2. *Frontiers in High Energy Density Physics - The X-Games of Contemporary Science* (National Academies Press, 2003);

3. *The Science and Applications of Ultrafast, Ultraintense Lasers: Opportunities in Science and Technology Using the Brightest Light Known to Man* (Report on the SAUUL Workshop, June 17-19, 2002); and

4. Pertinent technical reviews and federal advisory committee reports.

TASK FORCE WORKING GROUPS

A - HEDP in Astrophysical Systems
Rosner (Chair), Arons, Baring, Lamb, Stone

B - Beam-Induced HEDP (RHIC, heavy ion fusion, high-intensity accelerators, etc.) Joshi (Chair), Jacak, Logan, Mellisinos, Zajc

S - HEDP in Stockpile Stewardship Facilities (Omega, Z, National Ignition Facility, etc.) Remington (Chair), Deeney, Hammer, Lee, Meyerhofer, Schneider, Silvera, Wilde

U - Ultrafast, Ultraintense Laser Science
Ditmire (Chair), DiMauro, Falcone, Hill, Mori, Murnane

THRUST AREAS IN HIGH ENERGY DENSITY ASTROPHYSICS

HEDP Task Force

Thrust Area #1 - Astrophysical phenomena

What is the nature of matter and energy observed under extraordinary conditions in highly evolved stars and in their immediate surroundings, and how do matter and energy interact in such systems to produce the most energetic transient events in the universe?

Thrust Area #2 - Fundamental physics of high energy density astrophysical phenomena

What are the fundamental material properties of matter, and what is the nature of the fundamental interactions between matter and energy under the extreme conditions encountered in high energy density astrophysics?

THRUST AREAS IN HIGH ENERGY DENSITY ASTROPHYSICS

HEDP Task Force

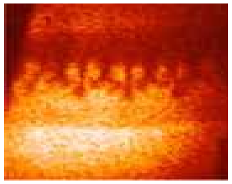
Thrust Area #3 - Laboratory astrophysics

What are the limits to our ability to test astrophysical models and fundamental physics in the laboratory, and how can we use laboratory experiments to elucidate either fundamental physics or phenomenology of astrophysical systems that are as yet inaccessible to either theory or simulations?

Laboratory astrophysics

- Motivating question:
  - What are the limits to our ability to test astrophysical models and fundamental physics in the laboratory; and how can we use laboratory experiments to elucidate either fundamental physics or phenomenology of astrophysical systems as yet inaccessible to either theory or simulations?
- The four key science objectives
  - Measuring material properties at high energy densities: equations of state, opacities, …
  - Building intuition for highly nonlinear astronomical phenomena, but under controlled lab conditions (with very different dimensionless parameters): radiation hydro, magnetohydrodynamics, particle acceleration, …
  - Connecting laboratory phenomena/physics directly to astrophysical phenomena/physics (viz., in asymptotic regimes for Re, Rm, …): late-time development of Type Ia and II supernovae, …
  - Validating instrumentation, diagnostics, simulation codes, … , aimed at astronomical observations/phenomena

Type II SN shock simulation (Kifonidis et al. 2000)



Type II SN shock experiment (Robey et al. 2001)

THRUST AREAS IN BEAM-INDUCED HIGH ENERGY DENSITY PHYSICS

HEDP Task Force

Thrust Area #4 - Heavy-ion-driven high energy density physics and fusion

> **How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion ignition conditions?**

Thrust Area #5 - High energy density science with ultrarelativistic electron beams

> **How can the ultra-high electric fields in a beam-driven plasma wakefield be harnessed and sufficiently controlled to accelerate and focus high-quality, high-energy beams in compact devices?**

THRUST AREAS IN BEAM-INDUCED HIGH ENERGY DENSITY SCIENCE

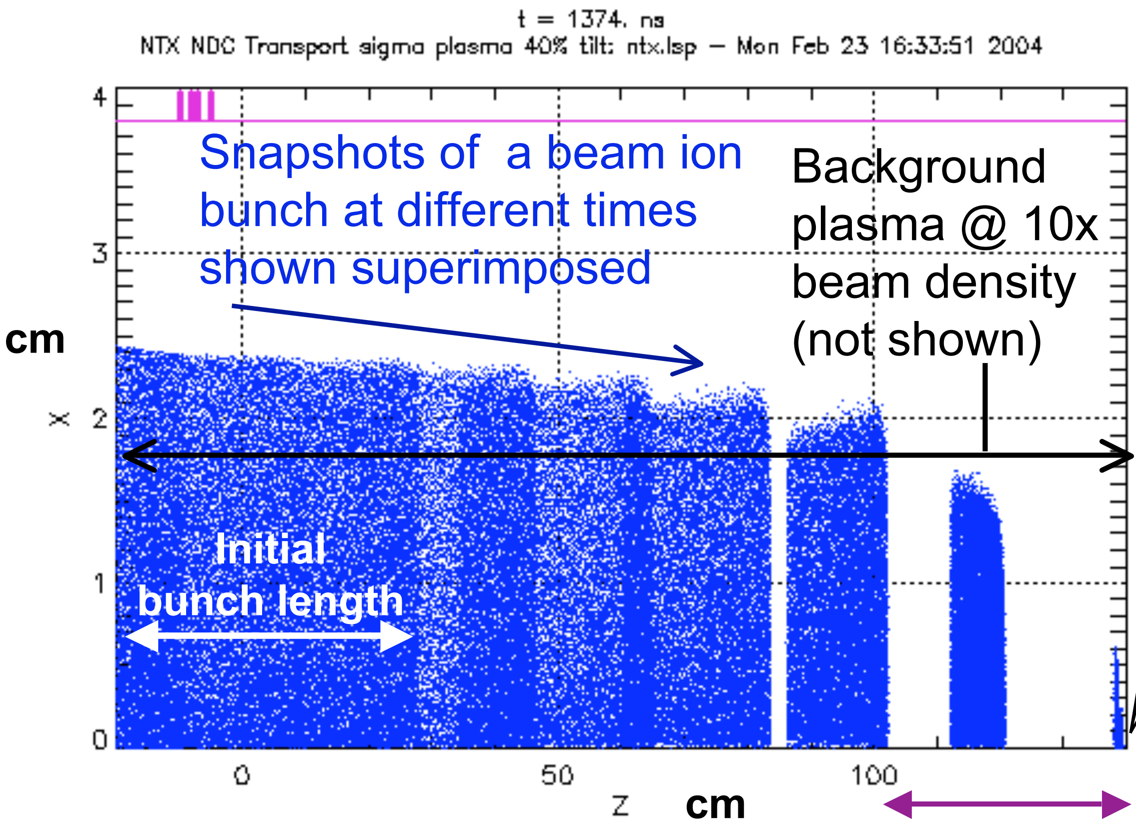
HEDP Task Force

Thrust Area #6 - Characterization of quark - gluon plasmas

What is the nature of matter at the exceedingly high density and temperature characteristic of the Early Universe?

Does the Quark Gluon plasma exhibit any of the properties of a classical plasma?

Simulations show large compressions of tailored-velocity ion beams in neutralizing background plasma



←Ramped 220-390 keV K^+ ion beam injected into a 1.4-m -long plasma column:

- Axial compression 120 X
- Radial compression to 1/e focal spot radius < 1 mm
- *Beam intensity on target increases by 50,000 X.*

Existing 3.9T solenoid focuses beam

- **Velocity chirp amplifies beam power analogous to frequency chirp in CPA lasers**
- **Solenoids and/or adiabatic plasma lens can focus compressed bunches *in plasma***
- **Instabilities may be controlled with $n_p >> n_b$, and B_z field (Welch, Rose, Kaganovich)**

Physics of Quark - Gluon Plasmas

- **Create high(est) energy density matter**
  - Similar to that existing ~1 msec after the Big Bang.
  - Can study only in the lab – relics from Big Bang inaccessible.
  - T ~ 200-400 MeV (~ 2-4 x 10^{12} K).
  - U ~ 5-15 GeV/fm^3 (~ 10^{30} J/cm^3).
  - R ~ 10 fm, t_{life} ~ 10 fm/c (~3 x 10^{-23} sec).

- **Characterize the hot, dense medium**
  - Expect quantum chromodynamic phase transition to quark gluon plasma.
  - Does medium behave as a plasma? coupling weak or strong?
  - What is the density, temperature, radiation rate, collision frequency, conductivity, opacity, Debye screening length?
  - Probes: passive (radiation) and those created in the collision.

HIGH ENERGY DENSITY THRUST AREAS IN STOCKPILLE STEWARDSHIP FACILITIES

HEDP Task Force

Thrust Area #7 - Materials properties

What are the fundamental properties of matter at extreme states of temperature and/or density?

Thrust Area #8 - Compressible dynamics

How do compressible, nonlinear flows evolve into the turbulent regime?

HIGH ENERGY DENSITY THRUST AREAS IN STOCKPILLE STEWARDSHIP FACILITIES

HEDP Task Force

Thrust Area #9 - Radiative hydrodynamics

Can high energy density experiments answer enduring questions about nonlinear radiative hydrodynamics and the dynamics of powerful astrophysical phenomena?

Thrust Area #10 - Inertial confinement fusion

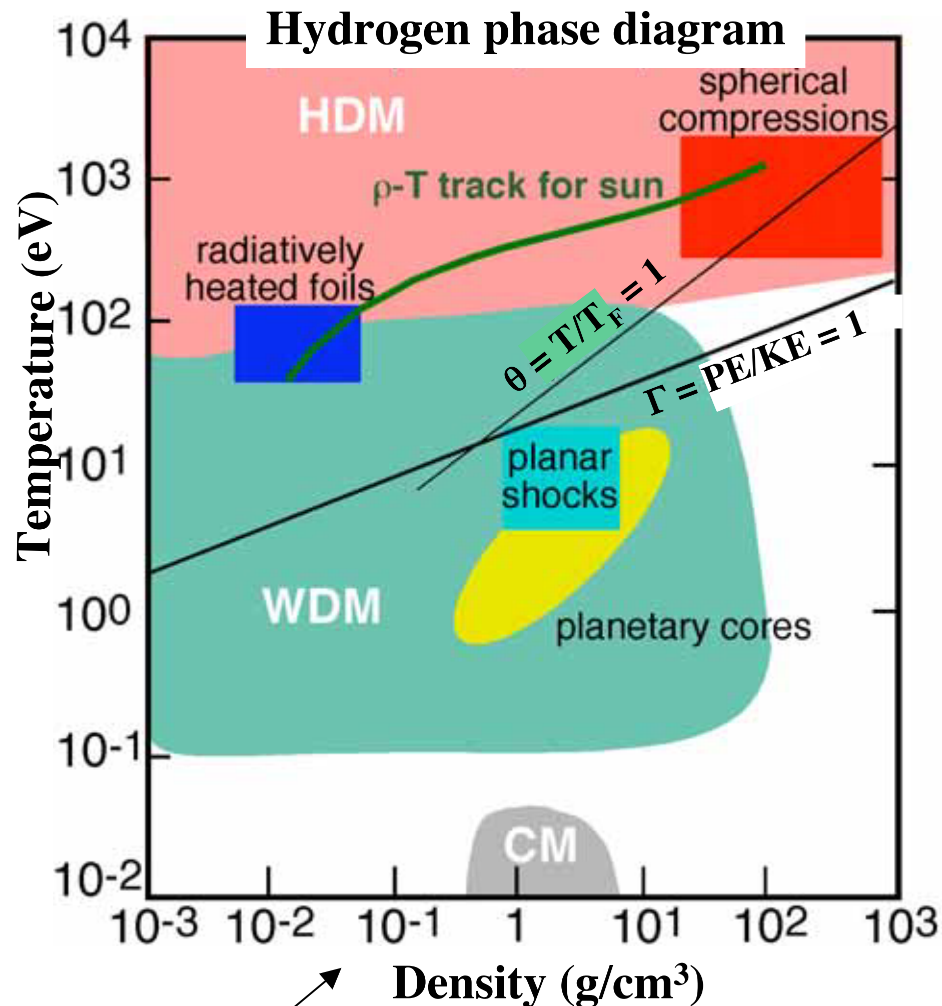
Can inertial fusion ignition be achieved in the laboratory and developed as a research tool?

The Material Properties thrust encompasses the study of fundamental properties of matter under extreme states of density and temperature

- **Material Properties describe:**
  - Equation of State (EOS)
  - Radiative opacity
  - Conductivity, viscosity, …
  - Equilibration time

- **Hot Dense Matter (HDM) occurs in:**
  - Stellar interiors, accretion disks
  - Laser plasmas, Z-pinches
  - Radiatively heated foams
  - ICF capsule implosion cores

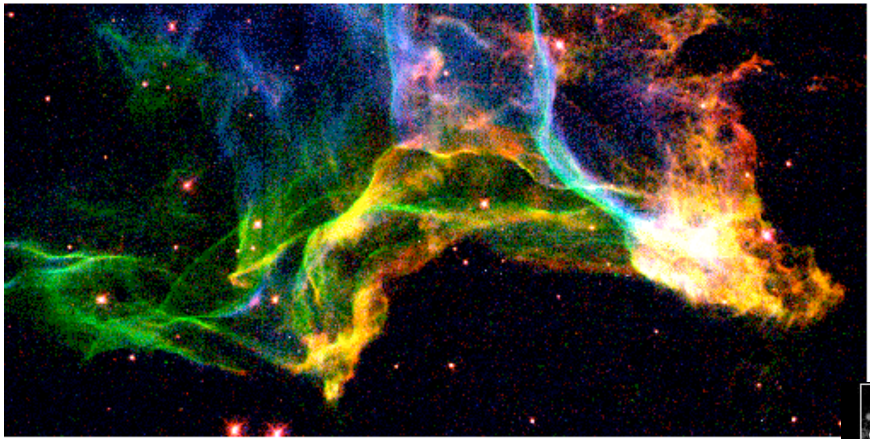
- **Warm Dense Matter (WDM) occurs in:**
  - Cores of giant planets
  - Strongly shocked solids
  - Radiatively heated solid foils



- **Tenuous plasma "easy": Γ = PE/KE << 1;**
- **Dense plasma "difficult": $\Gamma \sim 1$ and $\theta \sim 1$**

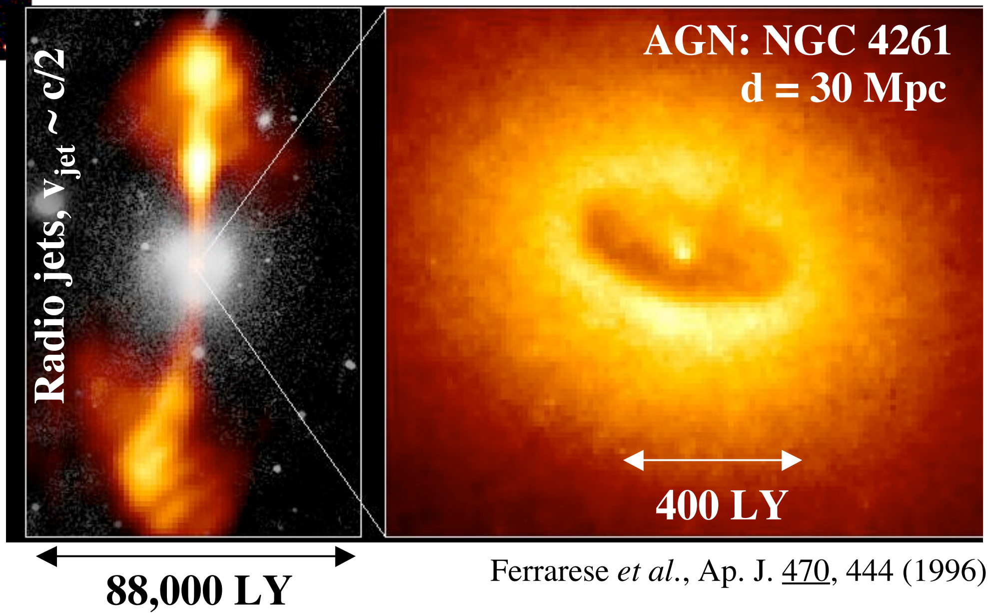
Radiative hydrodynamics abound in energetic astrophysics

Radiative shocks in the Cygnus Loop supernova remnant (SNR)



Photoionized plasmas in an accreting massive black hole

Piner *et al.*, A.J. 122, 2954 (2001)



Ferrarese *et al.*, Ap. J. 470, 444 (1996)

- **Additional examples of radiative hydrodynamics in astrophysics:**

  - **Radiatively cooled jets**

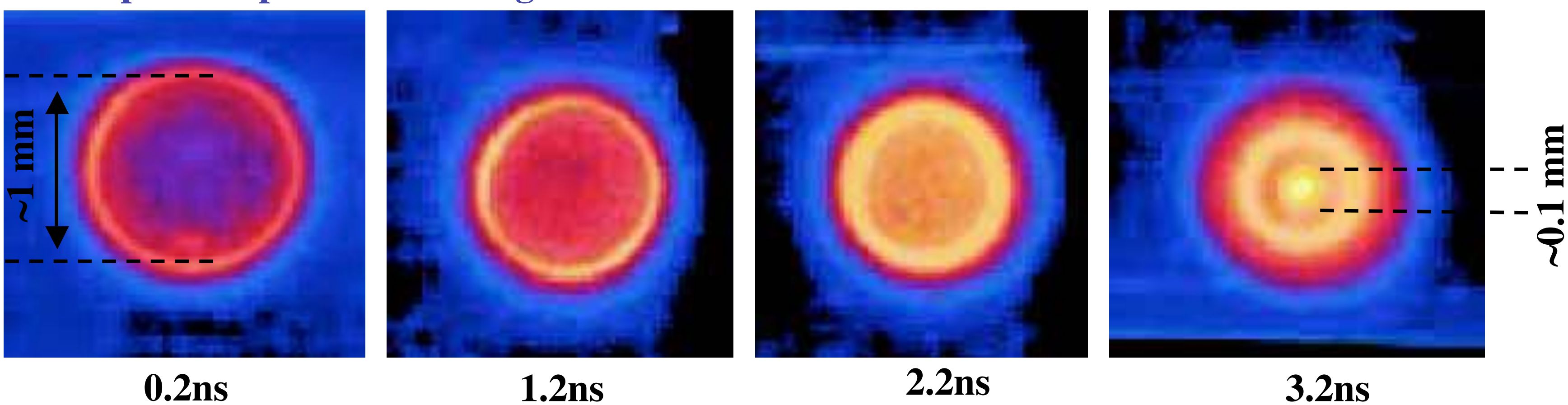
  - **Radiatively driven molecular clouds**

- **Our understanding of these phenomena would improve significantly if we could develop scaled radiative hydrodynamics experimental testbeds to validate modeling**

The Inertial Confinement Fusion (ICF) thrust is focused on achieving thermonuclear ignition within the decade

- The achievement of ignition and gain is a a grand challenge goal of NNSA.
- Ignition experiments will commence on the NIF laser at Livermore in about 2010.
- Supporting experiments and physics development are carried out on OMEGA (UR-LLE), Z/ZR (SNL), and smaller facilities.

ICF capsule implosion on Omega



- ICF research involves a multitude of coupled phenomena, all occurring in a few nanoseconds on sub-millimeter spatial scales
    - -Laser coupling, laser-plasma instabilities, hydrodynamic instabilities,
    - -radiation transport, electron heat transport, thermonuclear fusion reactions

THRUST AREAS IN ULTRAFAST ULTRAINTENSE LASER SCIENCE

Thrust Area #11 - Laser excitation of many-particle systems at the relativistic extreme

How do many-body systems evolve in a light field under extreme relativistic conditions where an electron is accelerated to relativistic energies and particle production becomes possible in one optical cycle?

Thrust Area #12 - Attosecond physics

Can physical and chemical processes be controlled with light pulses created in the laboratory that possess both the intrinsic time- (attoseconds, 1 as = 10^{-18} s) and length- (x-rays, 1 Å) scales of all atomic matter?

THRUST AREAS IN ULTRAFAST ULTRAINTENSE LASER SCIENCE

HEDP Task Force

Thrust Area #13 - Ultrafast, high-peak-power x-rays

Can intense, ultra-fast x-rays become a routine tool for imaging the structure and motion of "single" complex bio-molecules that are the constituents of all living things?

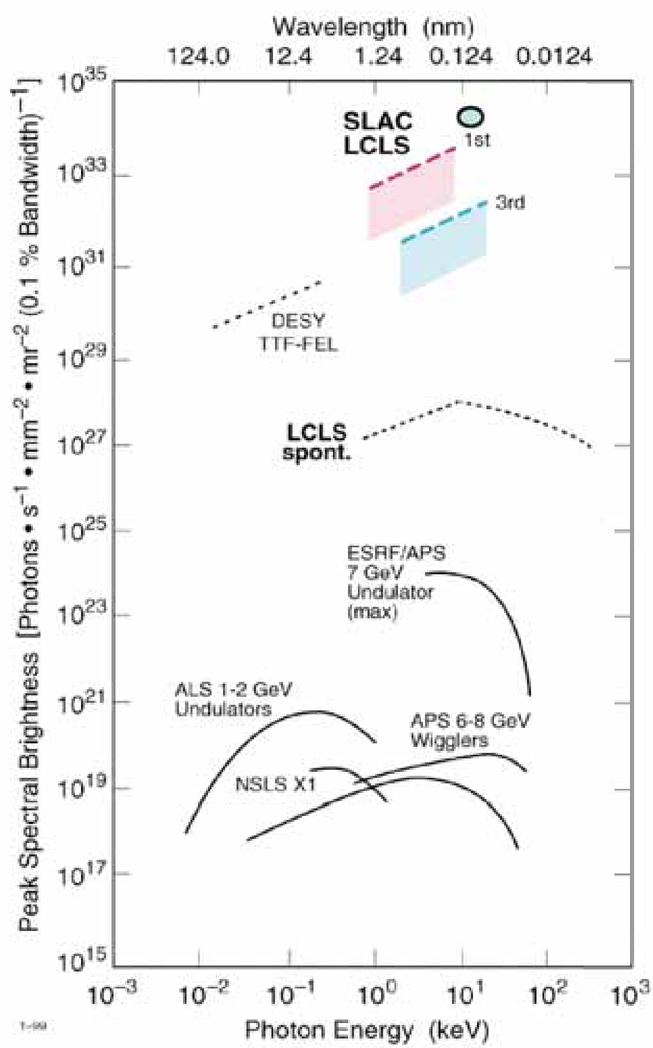
Can nonlinear optics be applied as a powerful, routine probe of matter in the XUV/x-ray regime?

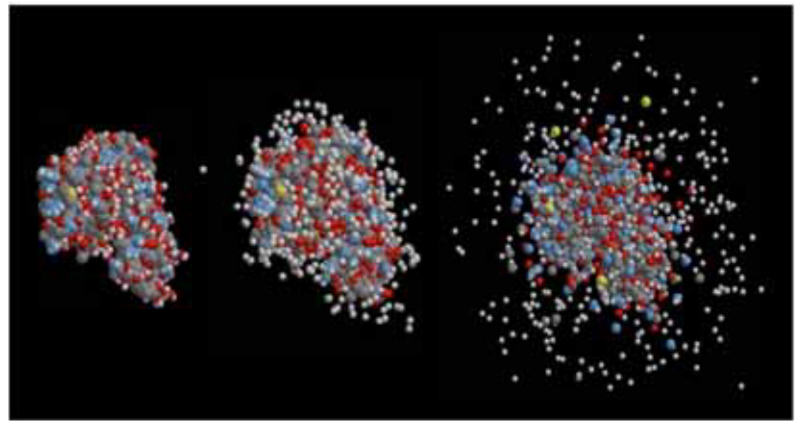
Thrust Area #14 - Compact high energy particle acceleration

How can ultra-intense ultra-short pulse lasers be used to develop compact GeV to TeVclass electron and or proton/ion accelerators?

The LINAC Coherent Light Source (LCLS) will revolutionize ultrafast x-ray science

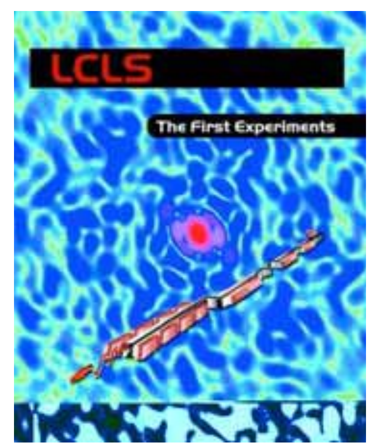
HEDP Task Force





"potential for biomolecular imaging with femtosecond x-ray pulses"
Neutze R, Hajdu J et al., Nature 406, 752 (2000).

Baseline performance:
- 15-1.5 Angstrom
- 10 GW peak power
  larger by 10^9 to current sources
- ultra-short, 200 fs - ???
  exceeds 3[rd] generation by ≥ 10^3
- coherent
  large degeneracy factor ≥ 10^9



THRUST AREAS IN ULTRAFAST ULTRAINTENSE LASER SCIENCE

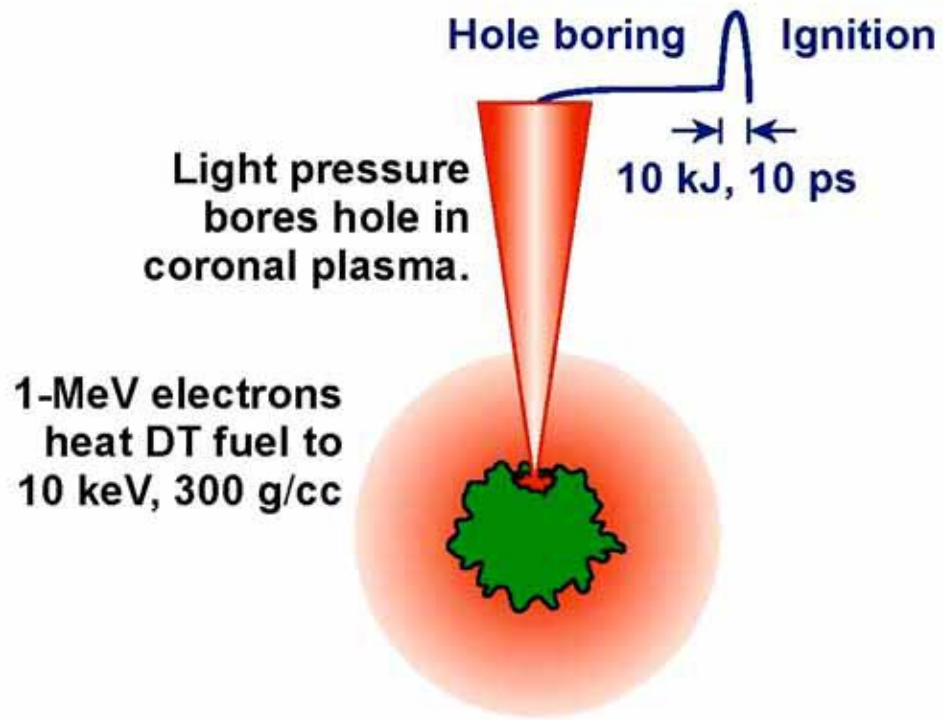
HEDP Task Force

Thrust Area #15 - Inertial fusion energy fast ignition

Is it possible to make controlled nuclear fusion useful and efficient by heating plasmas with an intense, short pulse laser?

Fast Ignition offers the potential to increase target gains and reduce driver energy requirements

- The Fast Ignition concept was proposed in 1994
- In Fast Ignition, the compression and heating processes are separated.
- Preliminary experiments, including integrated ones at ILE, continue to increase confidence in this concept.
- All three of the large NNSA HED facilities are planning to add high energy petawatt capability.
- These combined facilities will address the fundamental question:



Will the Fast Ignition concept lead to higher target gains for the same driver energy?

CONCLUSIONS

HEDP Task Force

High energy density plasma science is a rapidly growing field with enormous potential for discovery in scientific and technological areas of high intellectual value.

The opportunities for graduate student training, Postdoctoral research, commercial spin-offs, and interdisciplinary research are likely to increase for many decades to come.

Back-up Vugraphs

U.S. Department of Energy

Office of Science

DOE/OFES Perspectives

Presented to

Inaugural IFE Science and Technology Strategic Planning Workshop: Updates on Progress, Visions, and Near-Term Opportunities
San Ramon, California April 24 - 27, 2007

Office of Fusion Energy Sciences

Excellent Science Attractive Energy

Raymond Fonck
Associate Director
of Fusion Energy Sciences
April 25, 2007

www.science.doe.gov/ofes

U.S. Fusion Energy Sciences Program Elements

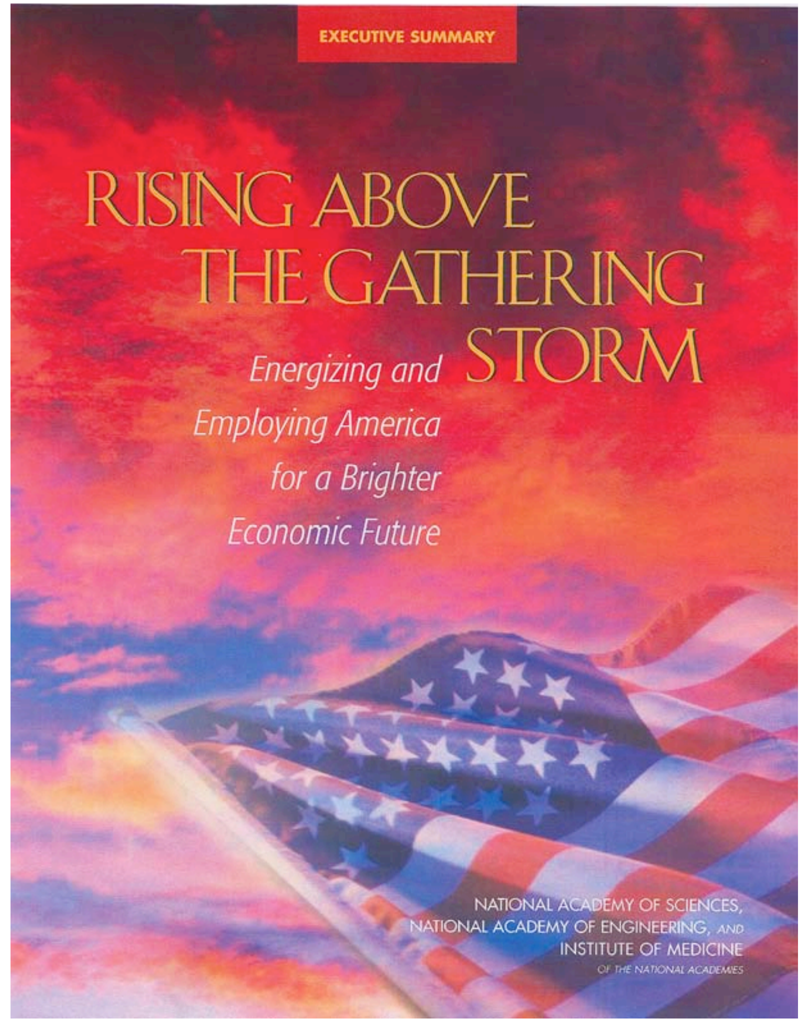
- Stewardship of Plasma Science
- Joint Program for High Energy Density Laboratory Physics (w/NNSA)
- Fusion Energy Science and Technology

Office of Fusion Energy Sciences
Excellent Science Attractive Energy

An Opportunity for Growth… and a Challenge

National Academy of Sciences Report:

Fusion is part of SC's part of the American Competitiveness Initiative (& Advanced Energy Initiative)



Office of Fusion Energy Sciences
Excellent Science Attractive Energy

FES Program Must Compete in ACI World

- **Domestic fusion activities will evolve to compete in this new era**
  - Participation in ITER sets a new scale for magnetic fusion science
    - Collaborative world-wide program
  - Reflect advances in HEDP/ICF/IFE
  - Promoting Plasma Science and HEDLP
  - Requires a world-leading domestic fusion science program

- **Significant challenges need to be addressed**
  - Workforce issues over decades
  - Aging facilities (MFE); Many HEDP/IFE facilities outside FES
  - “Grid-locked” funding
  - Continuing community development towards science focus

- **Need to revisit strategic plan or scientific roadmap for FES**
  - New Initiatives (e.g., HEDLP Joint Program) need definition

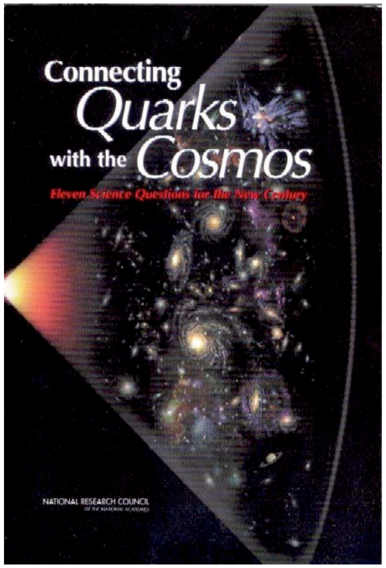
Suggestions Towards a Strategic Plan…

- **Vision:**
  - The FES Program supports world-leading science and technical research to develop the knowledge base for an attractive fusion energy source, and supports leading research in the fundamental areas of Plasma Physics and High Energy Density Physics

- **Goals:**
  - Steward the field of Plasma Physics as a fundamental physical science
  - Collaboratively steward High Energy Density Laboratory Physics (HEDLP) as an emerging new field of physics
  - Create the knowledge base that society/industry can use to develop a 1st-generation fusion energy facility on the ITER timeframe
  - Development of fusion science to ensure success and facilitate future 2nd-generation fusion energy concepts

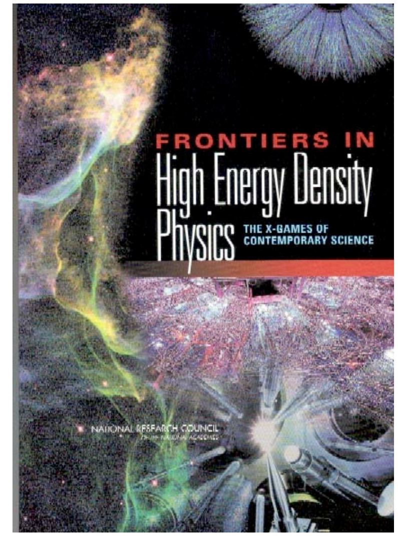
- **Achieving these Goals:**
  - Where are we now: what elements do we have in place?
  - What more do we need?

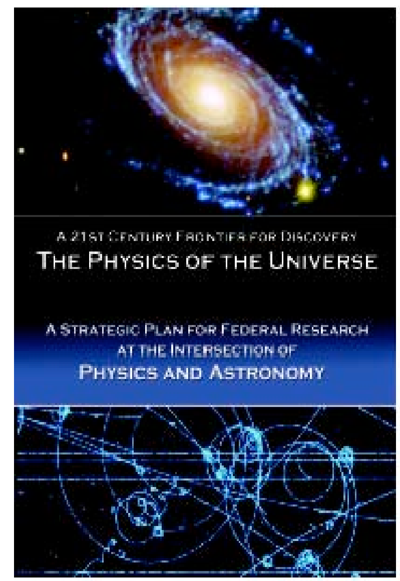
Reports on HEDP Spurred Interest



- Turner's NRC Report 2003 "Connecting Quarks with the Cosmos"
- Davidson's NRC Report 2003 "Frontiers in High Energy Density Physics: X-Games of Contemporary Physics"
- Community Workshop Report 2003 on "The Science and Applications of Ultrafast, Ultraintense Lasers"
- Report of the Interagency Working Group on the Physics of the Universe (IWG-POU), "A 21st Century Frontier for Discovery: The Physics of the Universe"
  - The field of HEDP is compelling
  - "In order to develop a balanced, comprehensive program, NSF will work with DOE, NIST and NASA to develop a science driven roadmap that lays out the major components of a national HEDP program, …."

•An interagency Task Force on HEDP (TF-HEDP) was chartered to recommend how to address scientific opportunites in HEDP





The Joint Program in HEDLP

- OFES and NNSA ICF Office establishing a joint program in High Energy Density Laboratory Plasmas (HEDLP)
  - *Addressing the finding of the interagency TF-HEDP*
  - *The joint program will provide stewardship of HEDLP while maintaining the interdisciplinary nature of this area of science*
- Topical research areas include:
  - *Laboratory astrophysics*
  - *Compressible dynamics and radiative hydrodynamics*
  - *Heavy ions, warm dense matter and strongly coupled plasmas*
  - *Dense plasmas in ultrahigh magnetic fields*
  - *Laser-plasma interactions*
  - *Inertial confinement fusion and fast ignition*
  - *HEDLP with ultra-fast and ultra-intense lasers*

What's Next for the Joint Program in HEDLP?

- Management plan for the joint program under discussion between OFES and NNSA
  - *Interagency Task Force on HEDP report due soon*
- An Advisory Committee to be identified
- Series of Workshops initiated
  - *Help design a compelling research plan for HEDLP*
- Budget Request for FY 2009 to be prepared for joint program
- Solicitations to be issued in FY 2008 to compete for FY 2009 funds

Office of Fusion Energy Sciences
Excellent Science Attractive Energy

The Joint Program in HEDLP: FES

- Current HEDP program in OFES includes:
  - Research in fast ignition
  - Laser-plasma interactions
  - Dense plasmas in ultrahigh magnetic fields
  - Heavy ions
  - Strongly coupled plasmas

- Scope and/or depth of the program will expand and grow with funding
  - This Workshop, plus upcoming DOE Workshops
  - Need help to describe the Science Roadmap that parallels previous Development Roadmaps…
    - New science opportunities need to be identified

Excellent Science Attractive Energy
Office of Fusion Energy Sciences

5-Year Plan Sent to Congress

	FY 2007	FY 2007	FY 2008	FY 2009	FY 2010	FY 2011	FY 2012
	CONG	**Mar AFP**	**CONG**				
Facility Operations	64,725	63,857	68,699	80,484*	84,126	83,674	86,653
ITER TPC	60,000	60,000	160,000	214,500	209,321	181,964	130,000
NCSX MIE	15,900	15,822	15,900	2,264			
Core Research	178,325	179,271	183,251	190,274	202,801	214,274	224,280
FES Total	**318,950**	**318,950**	**427,850**	**407,038**	**496,248**	**479,912**	**440,933**

Excellent Science
Attractive Energy
Office of
Fusion
Energy
Sciences

Fusion Energy Sciences
($ in thousands)

	FY 2006 Actuals	FY 2007 CONG	FY 2008 CONG
Science			
DIII-D Research	24,274	24,300	25,264
C-MOD Research	8,490	8,890	9,133
International Collaborations	4,951	5,064	5,202
Diagnostics	3,763	3,854	3,959
Other	4,223	10,992	12,893
HBCU, Education, Outreach Reserves	(4,223)	(3,730)	(5,700)
SBIR/STTR (science)	0	(7,262)	(7,193)
Subtotal Tokamaks	45,701	53,100	56,451
NSTX Research	15,539	16,696	16,106
Experimental Plasma Research	21,389	19,990	20,638
HEDP	15,470	11,949	12,281
MST Research	6,445	6,970	6,970
NCSX Research	751	697	716
Subtotal Alternates Research	59,594	56,302	56,711
Theory	24,947	23,900	24,552
Advanced Computer/SciDAC	4,220	6,970	7,160
General Plasma Science	14,180	13,941	14,655
Science Total	148,642	154,213	159,529
Facility Operations			
DIII-D	30,780	32,362	34,405
Alcator C-Mod	13,032	13,941	14,322
NSTX	18,681	18,422	19,972
NCSX			
ITER			
Facility Ops times in weeks	7/14/11	12/15/12/0	15/15/12/0
NCSX MIE	17,019	15,900	15,900
GPP/GPE/ORNL Move	3,538	3,930	2,905
ACX			
ITER Preparation	5,294		
ITER MIE TEC Costs	15,866	37,000	149,500
Facility Operations Total	104,210	121,555	237,004

	FY 2006 Actuals	FY 2007 CONG	FY 2008 CONG
Enabling R&D			
Plasma Technologies	14,787	12,945	13,452
Advanced Design	2,529	2,550	2,550
Materials Research	7,066	4,687	4,815
ITER MIE OPC	3,449	23,000	10,500
Enabling R&D Total	27,831	43,182	31,317
Total Fusion Energy Sciences	280,683	318,950	427,850
Recap			
DIII-D Res+Ops	55,054	56,662	59,669
C-Mod Res+Ops	21,522	22,831	23,455
NSTX Res+Ops	34,220	35,118	36,078
NCSX Res+Ops			716
ITER Res+Ops			
Facility Res+Ops Total	110,796	114,611	119,918
ITER TPC	19,315	60,000	160,000
Total, Core R&D Total	261,368	258,950	267,850

- *HEDLP support has been modest…*

Office of Fusion Energy Sciences
Excellent Science Attractive Energy

A Few Summary Thoughts

- Need to craft a coherent vision with a matching scientific strategy to be competitive in the new ITER and NIF eras
  - Coordination of Low Density Plasmas/MFE and HEDLP/IFE interests will be challenging

- Stewardship of general plasma science and HEDLP are FES interests

- The fusion science program must…
  - be based on excellent science at all levels
  - establish the knowledge base for fusion energy
  - be nationally and internationally integrated
  - be world-leading in strategically selected areas

- The Joint HEDLP Initiative offers new opportunities
  - Anticipating new proposals and suggestions for this program
  - Need to work together to make case for added funding

Excellent Science Attractive Energy
Office of Fusion Energy Sciences

NNSA Overview

Presented at:
IFE Science and Technology
Strategic Planning Workshop

By:
Dr. Christopher J. Keane
Assistant Deputy Administrator for
Inertial Confinement Fusion and the NIF Project
National Nuclear Security Administration

April 25, 2007

Summary points

- The nuclear weapon complex is undergoing major changes (Complex 2030)
- Highest priority for ICF is NIF completion and execution of ignition experiments starting in FY2010
- Program is entering a scientific “golden age” with completion of ZR (2007), OMEGA EP (2008), and NIF (2009)
- NNSA/SC Joint Program in Laboratory High Energy Density Plasmas created to steward HEDLP within DOE
- NNSA is in process of implementing policy to run major facilities as “user facilities”
- Planning is underway for period beyond NIF ignition

Message to IFE Community

- Stewarding HEDLP is a priority for DOE – the greatest need is to enhance the community
- IFE-related science can be funded thru HEDLP
- Use NIF ignition, and other existing NNSA capabilities, to advance IFE target physics
- Apply existing NNSA-funded IFE capabilities to Stockpile Stewardship and HEDLP (including NIF ignition)
- NNSA is looking at advanced fusion goals for Stockpile Stewardship

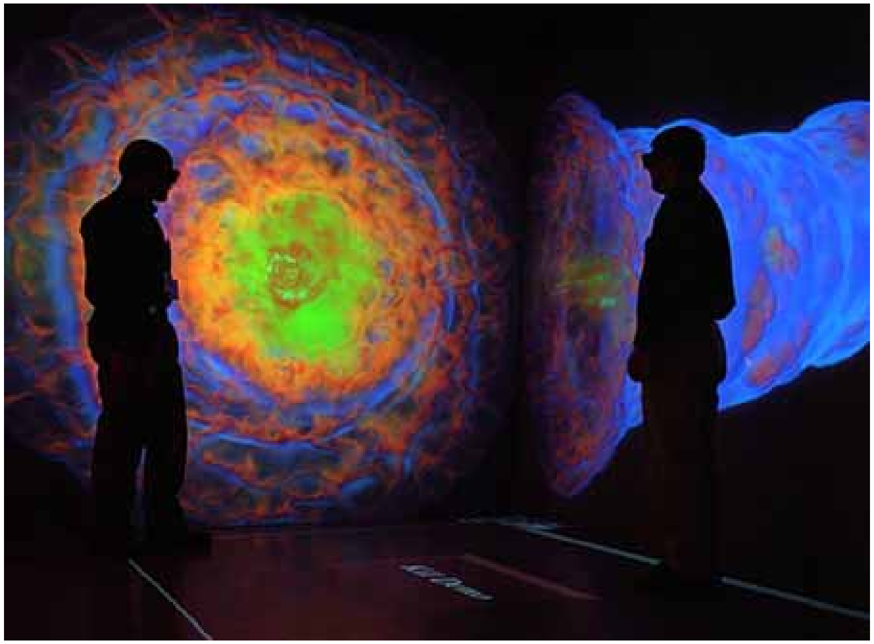
Complex 2030 relies on four long-term strategies and a near-term commitment

Long-term strategies

- In partnership with DoD, transform the nuclear stockpile.
- Transform to a modernized, cost-effective nuclear weapons complex.
- Create a fully integrated and interdependent nuclear weapons complex.
- Drive the science and technology base essential for long-term national security.

Near-term commitment

- Build confidence in the transformation process by "Getting the Job Done".



ICF and High Yield Campaign Strategic Objectives

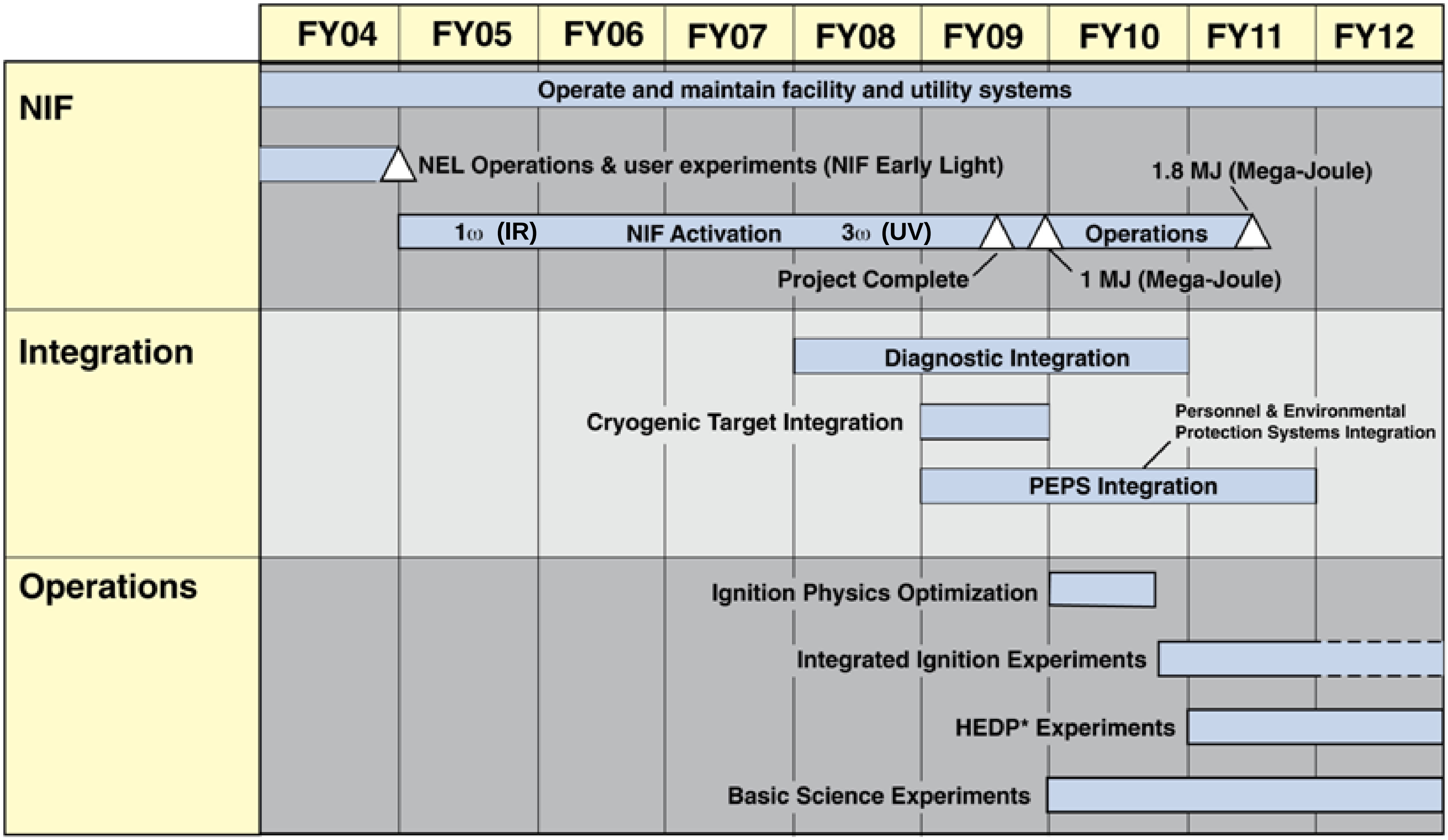
1. **Achieve ignition in the laboratory and develop it as a scientific tool for stockpile stewardship**

2. **Execute high energy density weapons physics experiments in support of stockpile stewardship in collaboration with other NNSA campaigns**

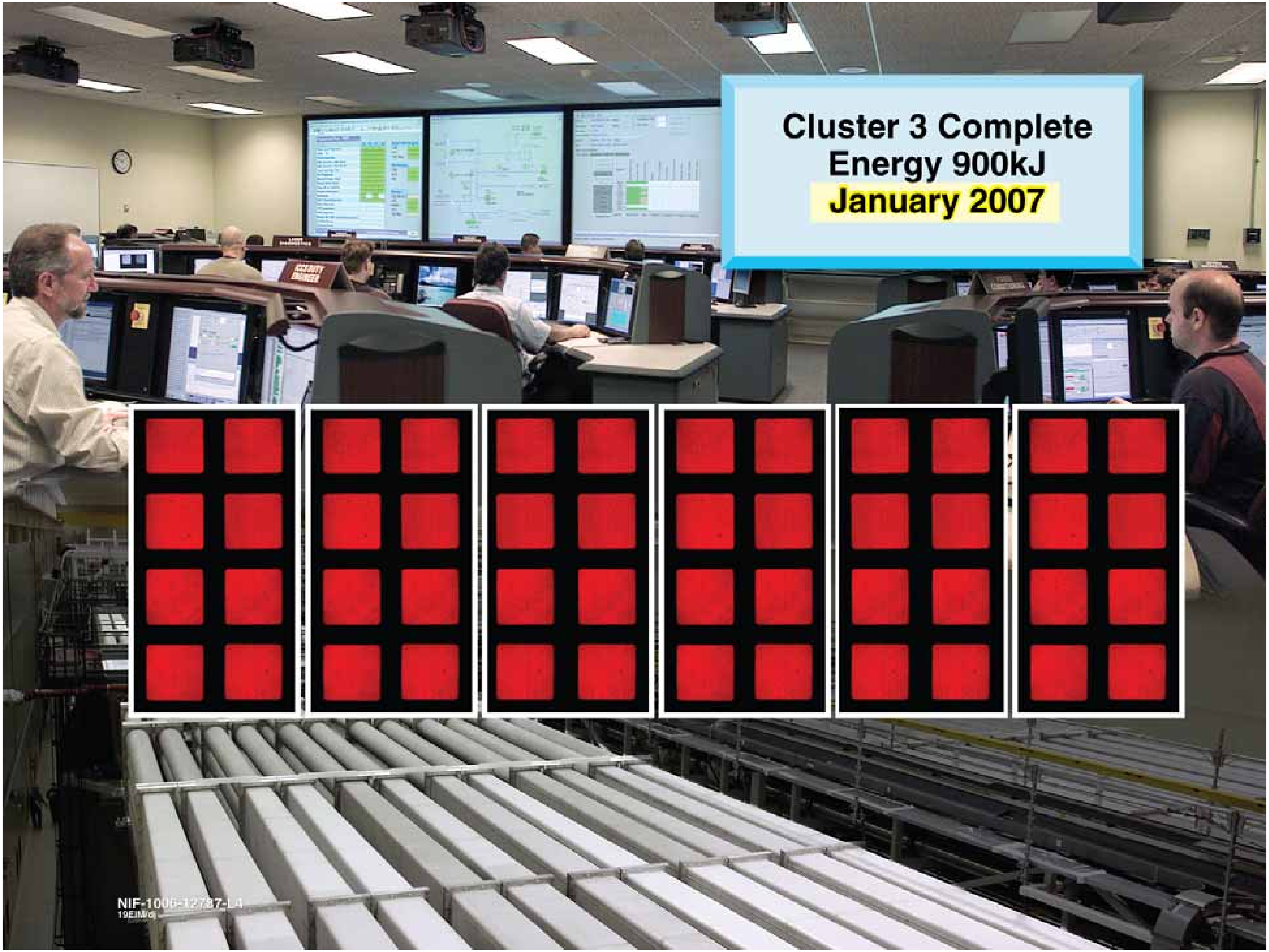
3. **Develop advanced concepts that support the long-term needs of stockpile stewardship**

4. **Steward the field of high energy density laboratory plasma physics (via joint program with DOE Office of Science)**

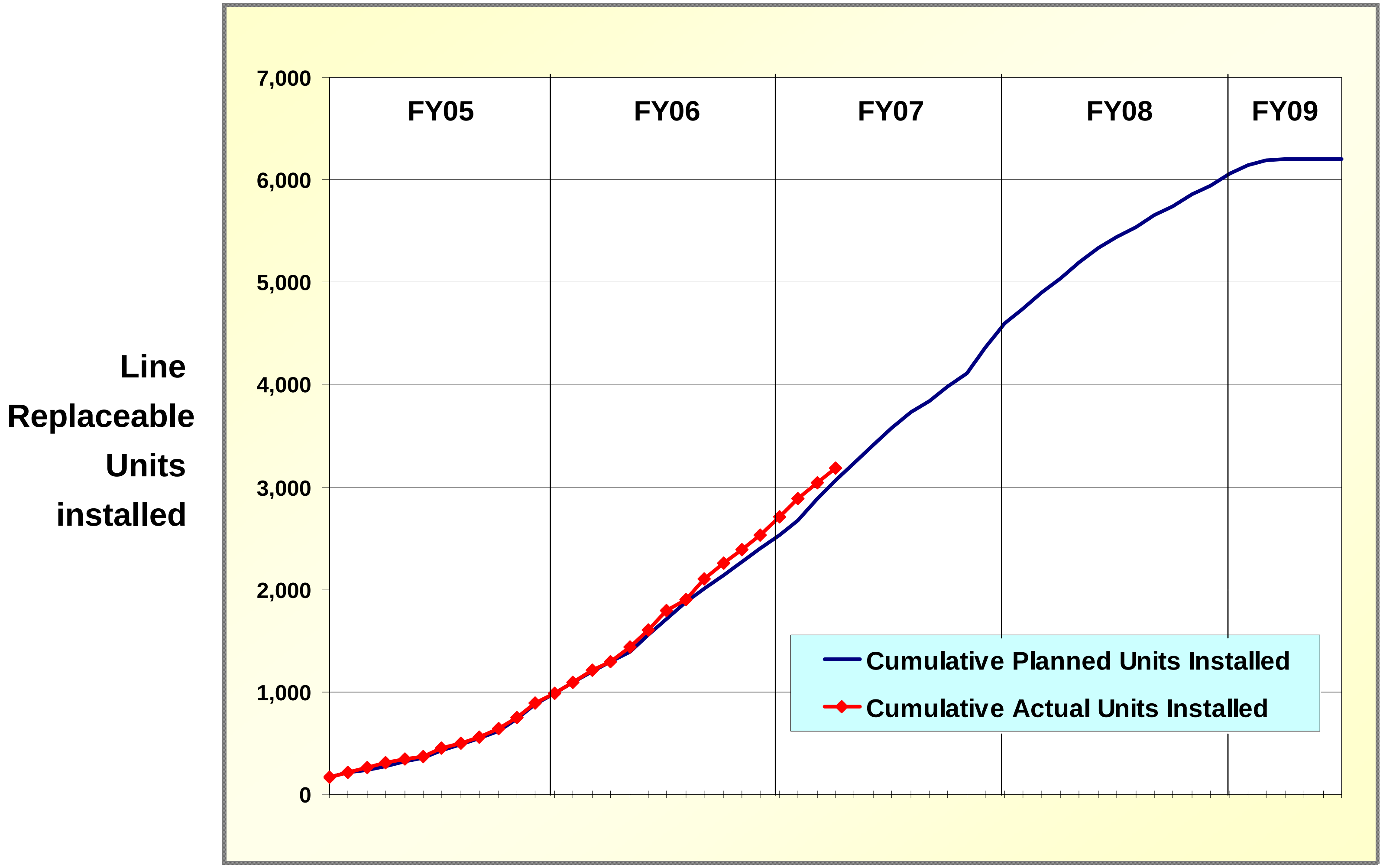
The plan for use of NIF calls for first ignition experiments in FY 2010



* Weapons physics experiments in support of Stockpile Stewardship


Cluster 3 Complete
Energy 900kJ
January 2007
NIF-1006-12787-L4
19EJM/dj

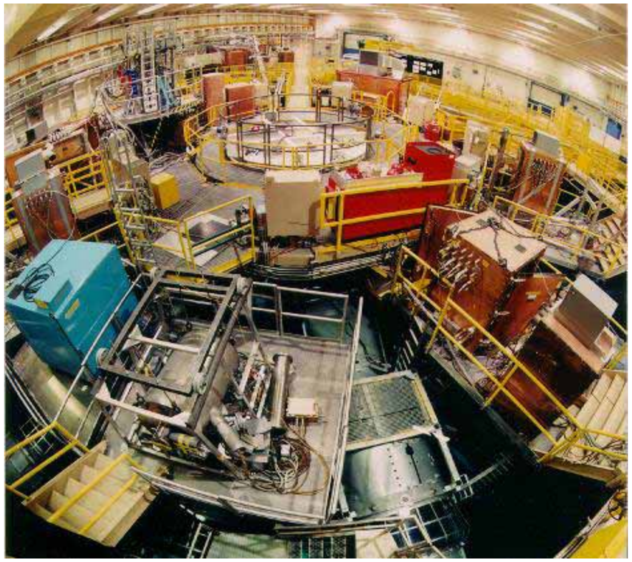
NIF is meeting its Line Replaceable Unit (LRU) Production and Installation Schedule



3,182 Line Replaceable Units (51%) were installed by December 31, 2006

Recent Progress on the Z Refurbishment Project

July 2006
(last shot)



September 2006
(dismantlement completed)

December 2006
(tank modifications completed)

- **Z has been dismantled**
- **Major tank modifications are complete**
- **Component installation began in January 2007**

January 15, 2007
(tank painting completed)

Sandia National Laboratories

OMEGA EP Laser Bay photo shows recent beamline progress

Joint Program in High Energy Density Laboratory Plasmas

- NNSA and Office of Science (OFES) have established a joint program in high energy density laboratory plasmas
- Purpose is to steward effectively this emerging field within DOE while maintaining the interdisciplinary nature of this area of science
- Program includes individual investigators, research centers activities, and user programs (National Laser User Facility program)
- Other agencies may join in the future (NSF, NASA)

Dollars in Thousands

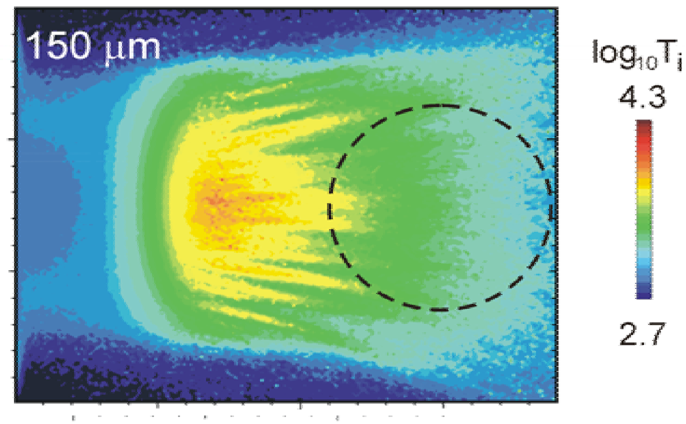
NNSA	**12,356**
User Facility Programs (fund via ICF Campaign)	1,613
Individual Investigators, Center Research, Grants & Fellowships (fund via Science & ICF Campaigns)	10,743
Office of Science (OFES)	**12,281**
Fast Ignition	2,840
High Mach Number Plasma Jets / Dense Plasmas in Ultrahigh Magnetic Fields	1,255
Heavy Ion Science	8,186
Total	**24,637**

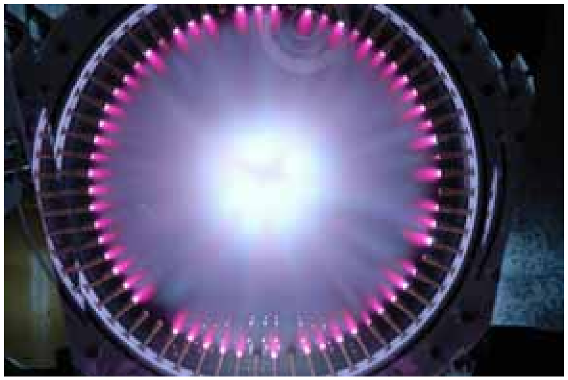
Key DOE finding: stewardship of HEDLP needs to be improved

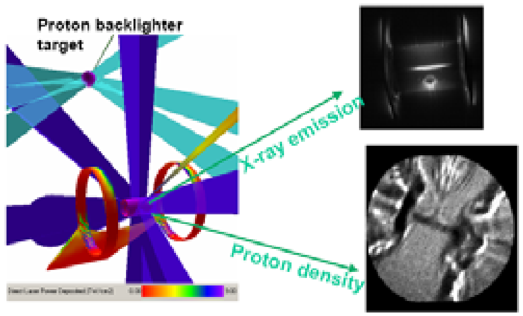
What characterizes a "well-stewarded" area of science?

- **Compelling scientific questions are clearly identified and prioritized (workshop process)**
- **Solicitations exist with adequate funding from clearly defined agency leads**
- **User facilities are established with program advisory committee process used to allocate time**
- **Facility user groups are active**
- **Federal advisory committees or other groups set strategic direction and build technical consensus on opportunities and priorities**
- **Scientific excitement is publicly visible**

Current OFES Program in HEDP
Y. C. Francis Thio







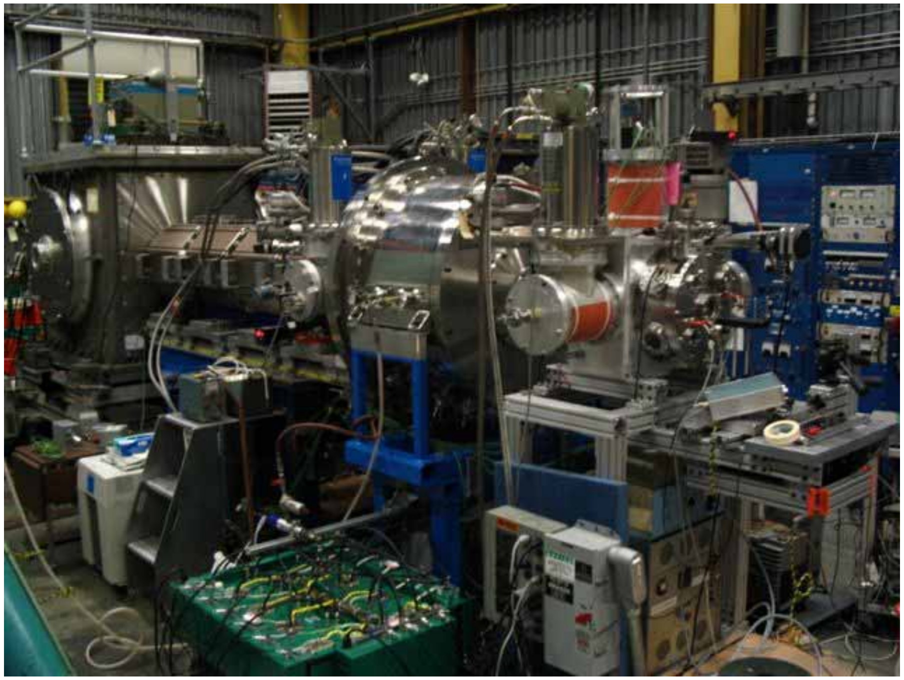
The Joint Program in HEDLP

- Scope and management plan under discussions between OFES and NNSA
- Topical research areas may include:
  - Strongly coupled plasmas, warm dense matter
  - Dense plasmas in ultrahigh magnetic fields
  - Laser-plasma interactions
  - Inertial confinement fusion and fast ignition
  - HED material Properties
  - HEDLP with ultra-fast and ultra-intense lasers
  - Laboratory astrophysics
  - Compressible dynamics and radiative hydrodynamics
- Scope and depth of the program may expand and grow with funding

Current HEDP Program in OFES

- Long-term goal of OFES is fusion energy – The present Fusion Energy Sciences program is science with a goal.
- SC has the following milestones in HEDP as part of its 20-year Strategic Plan for Fusion Energy Sciences:
  - Evaluate the feasibility of potential drivers, including heavy ion beams, dense plasma beams, and lasers as drivers for HEDP and IFE (2009)
  - Determine the physics limits that constrain the use of IFE drivers in key integrated experiments needed to resolve the scientific issues for IFE and high-energy density physics (2015)
- Performance Metric used by OMB for Fusion Energy Sciences in HEDP:
  - Progress toward developing the fundamental understanding and predictability of high energy density plasmas relevant to potential energy applications
- These requirements lead OFES to ask the following intellectual questions in its current HEDP program:
  - *How can inertial fusion be made more attractive (1) by decoupling compression and ignition, and/or (2) by the use of ultrahigh magnetic fields in the target plasma?*
  - *How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion ignition conditions?*

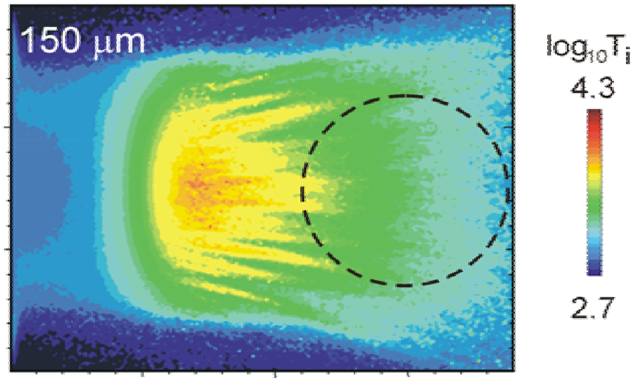
Heavy Ion Beam and Warm Dense Matter Research



- Currently, we are conducting research to explore the neutralized drift compression of heavy ion beams (NDCX).
- 60x longitudinal compression of the beam has been demonstrated.
- FY08 Funding: $8.2M

- Goal: By 2009, assess the physics limits of longitudinal and transverse compression of ion beams, and the technical issues of applying ion beams to research in warm dense matter, by performing exemplary beam-on-target experiments.

Fast Ignition as a study in Intense Laser-Matter Interaction and HED plasmas



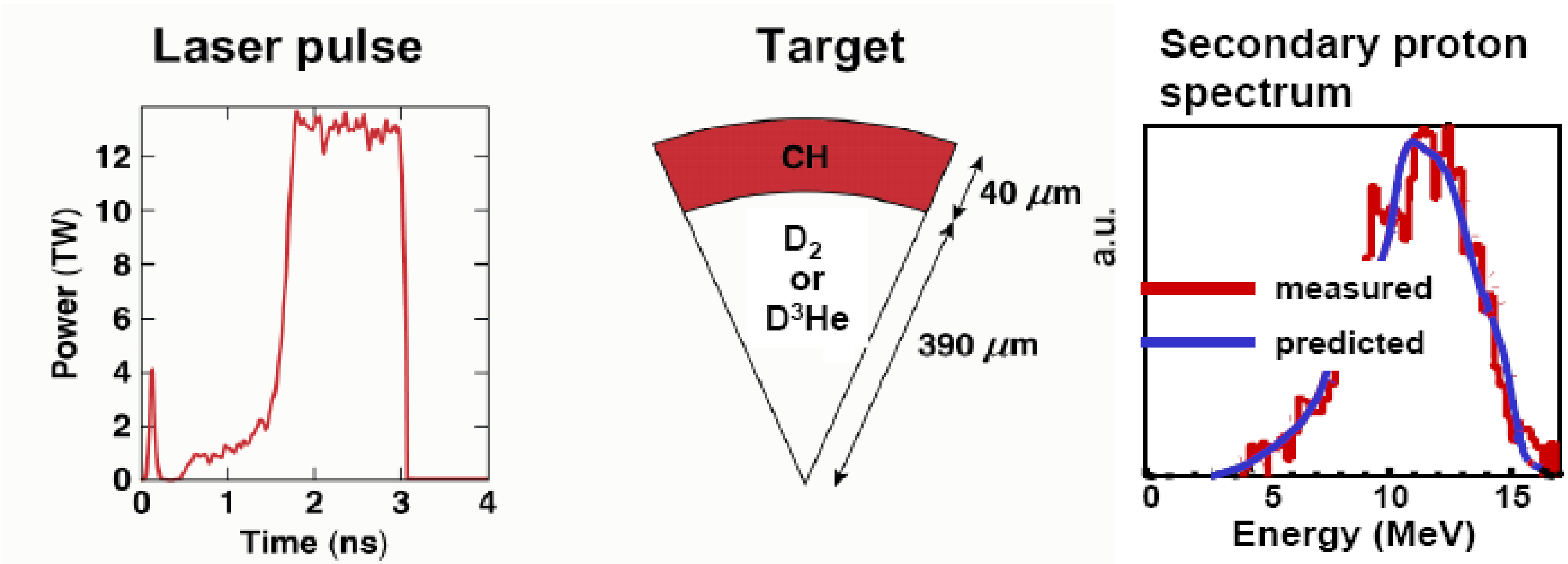
Honrubia et al

- Fuel assembly
- Laser-cone interaction to produce the relativistic electron jets
- Laser-target interaction to produce monoenergetic ion beams
- Transport of the electron jets or ion beams into the dense fuel

- Goal: By 2009, develop a working knowledge of the dominant physical processes governing fast ignition at a level sufficient for a design of a proof-of-principle experiment (Q > 0.1) for fast ignition on OMEGA-EP

Slow implosions with low adiabat were tested on OMEGA D-^{3}He fusion proton energy loss measured the high ρR

$E_L \approx 20$kJ $P \approx 25$-34atm $\alpha \approx 1.3$ $V \approx 2 \cdot 10^7$cm/s



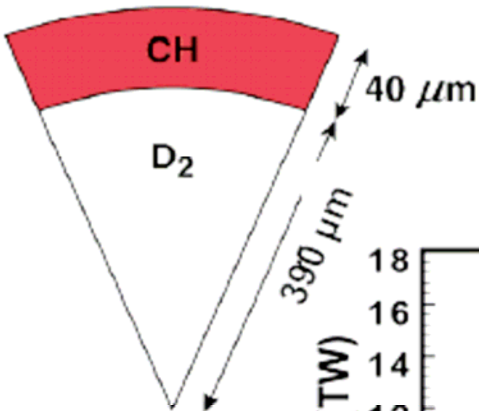
- Peak ρR is 0.26g/cm,^{2} the highest ρR to date on OMEGA
- Empty shells would achieve $\rho R \approx 0.7$g/cm^2 and stop 4MeV electrons

Warm (CH) thick-shell cone-target implosions in '08

C. Zhou, W. Theobald, R. Betti, P.B. Radha, V. Smalyuk, *et al*, Phys. Rev. Lett. 98: 025004 (2007)

The shock ignition concept has been tested on OMEGA

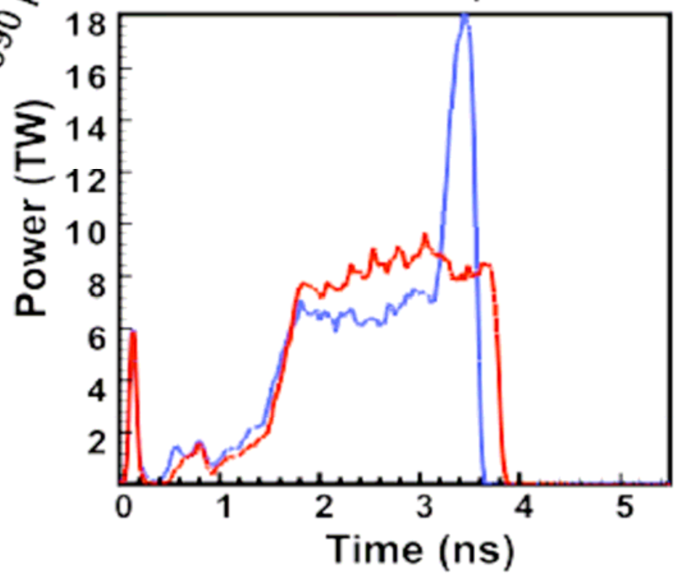
Target

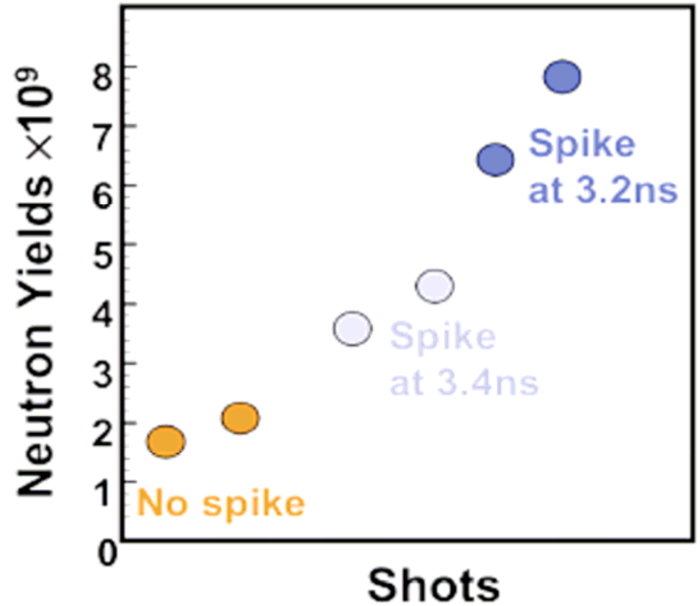


E_L=17-18kJ
$\alpha \approx 1.3$

W. Theobald,
R. Betti,
C. Zhou,
C. Stoeckl
(UR-LLE)

Pulse shape with and without shock spike

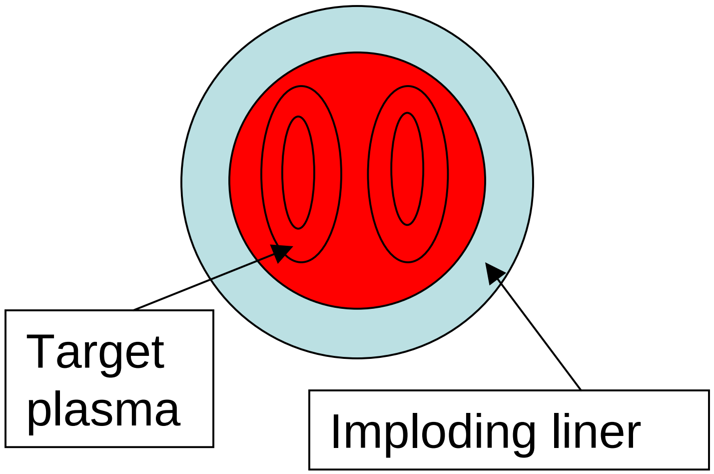




The neutron yield increases considerably when a shock is launched at the end of the pulse

More experiments with CH targets in '07-'08, cryo-targets in '09

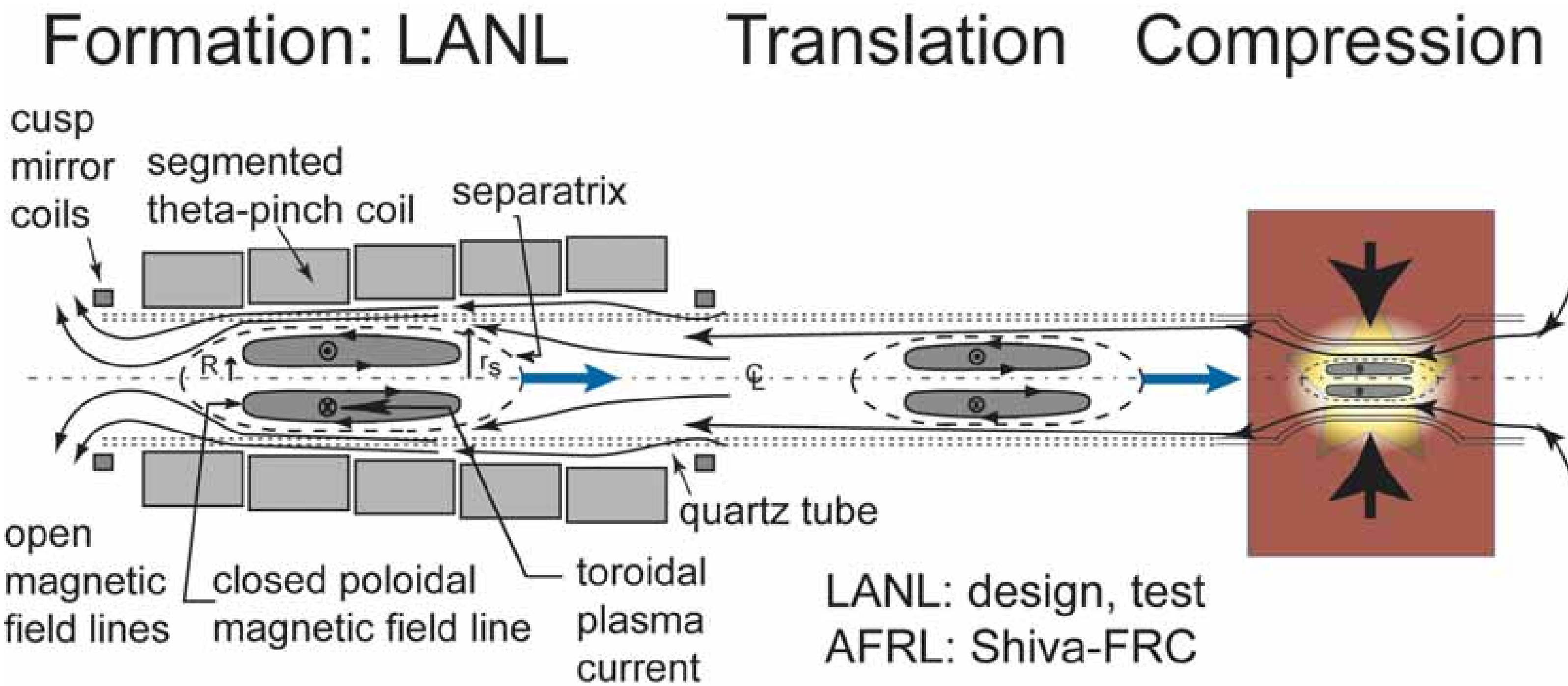
Emerging Concept: Magneto-Inertial Fusion as a study of Dense Plasma in Ultrahigh Magnetic Fields (B > 500 T)



- Uses a material shell (liner) to compress a plasma in which there is a seed magnetic field
- The liner is a magnetic flux conserver
  - Compression of the flux leads to increased magnetic field
- The magnetic field at peak compression is > 500 Tesla
  - The high B field suppresses cross-field thermal conduction
  - enhances alpha deposition in the target
- Uses inertial of the liner to provide plasma pressure confinement

- Goal: By 2009, identify and characterize the dominant physical processes governing magneto-inertial fusion; identify the physics issues and assess the feasibility of developing dense and high velocity plasma jets with Mach number greater than 10.

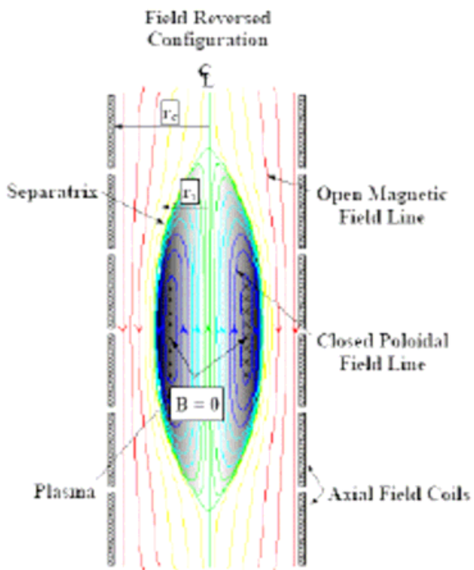
Solid-Liner Driven Magneto-Inertial Fusion FY2008….first physics demonstration of MIF

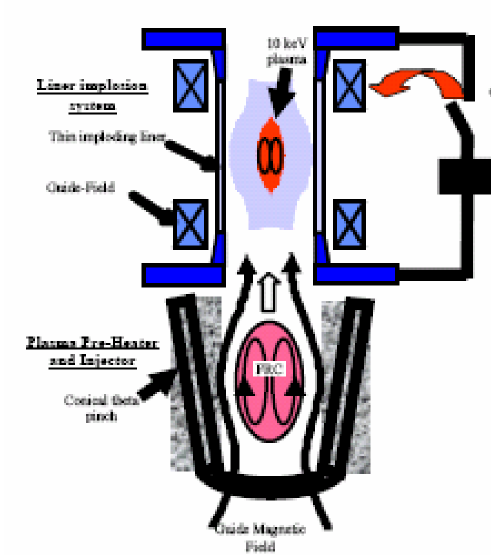


- Pulsed, high pressure approach to fusion
- Inertial + magnetic confinement
- Multi-keV fusion grade plasma

$2.2M in FY 2007

Accomplishments





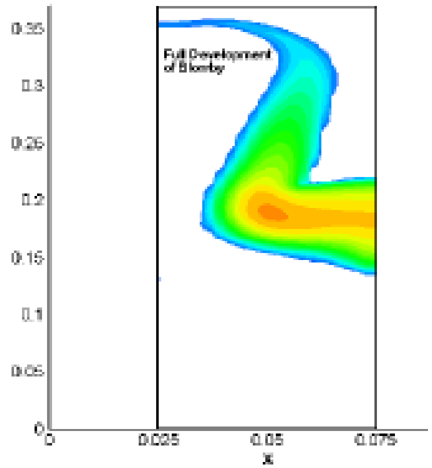
Typical parameters:		
	Initial	Final
n	$\sim 10^{17}$ cm^{-3}	$\sim 10^{19}$ cm^{-3}
T	~200 eV	~5 keV
B	~5 T	~500 T

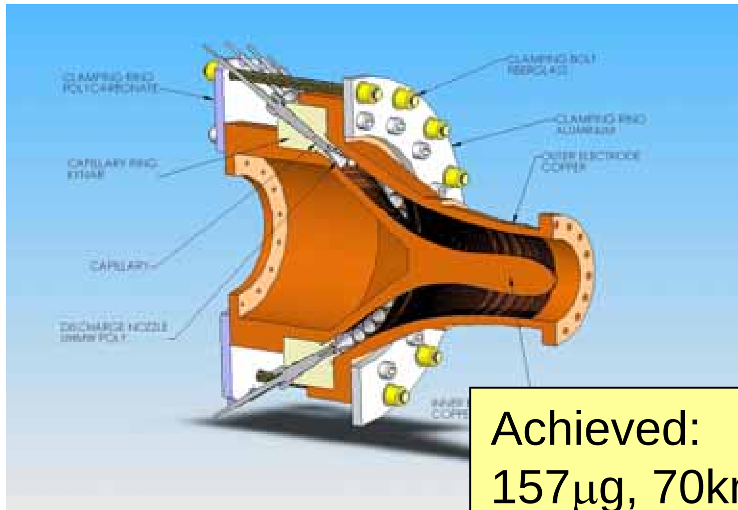
• Small, compact FRC formed with high density (~5 x 10^16 ion/cc), temperature > 200 eV with radii ~ 2 cm, suitable for implosion experiment. Historical FRC's are much lower density, larger size.

• Imploding liner experiments achieve suitable implosion features for FRC injection and compression to MTF conditions (size, velocity, symmetry, lack of instability growth, radial convergence, and sufficiently large electrode apertures)

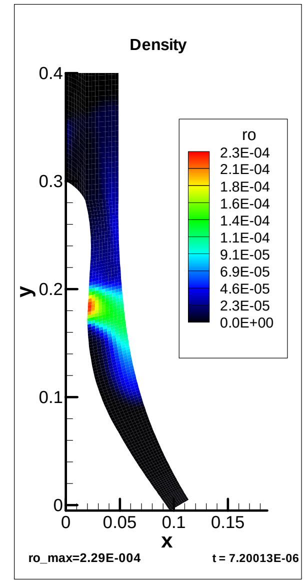
•2D-MHD simulations of FRC formation, translation., and compression indicate potential for compressing magnetized plasmas to density ~ 10^19 ions/cc, T ~ 5 KeV, n-tau ~ 10^12 – 10^13 sec/cc

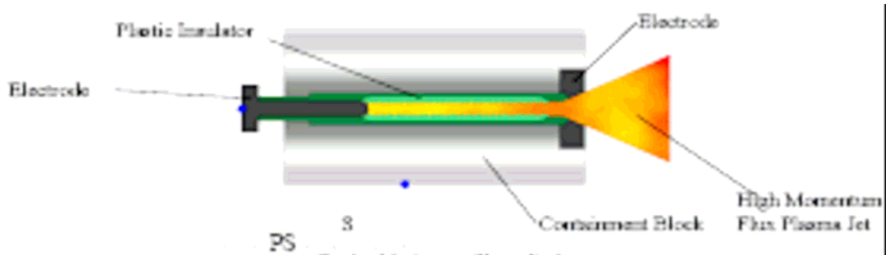
Development of High Mach Number Plasma Jets



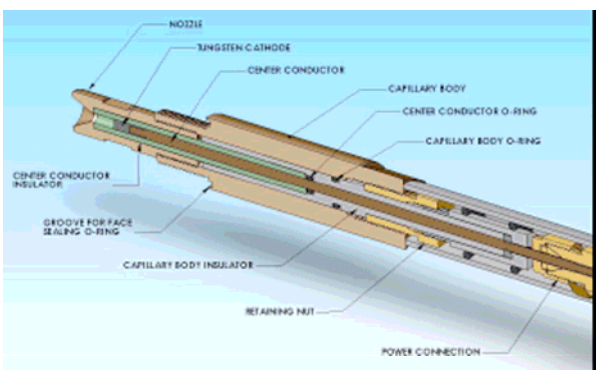


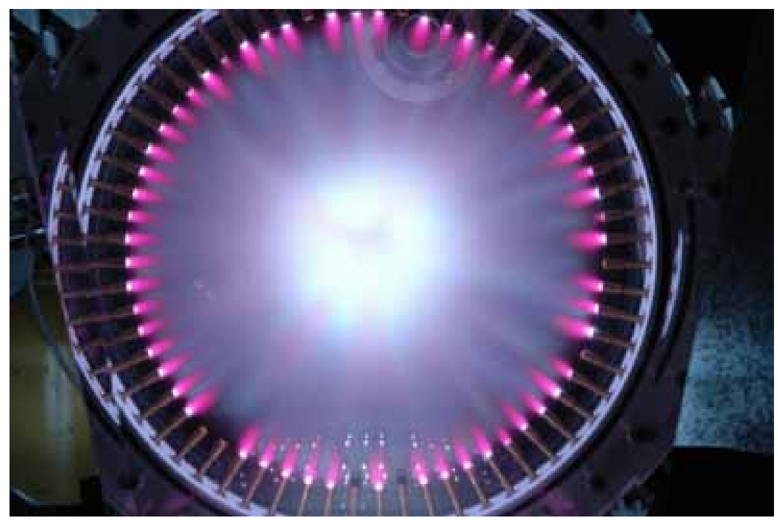
Achieved:
157μg, 70km/s



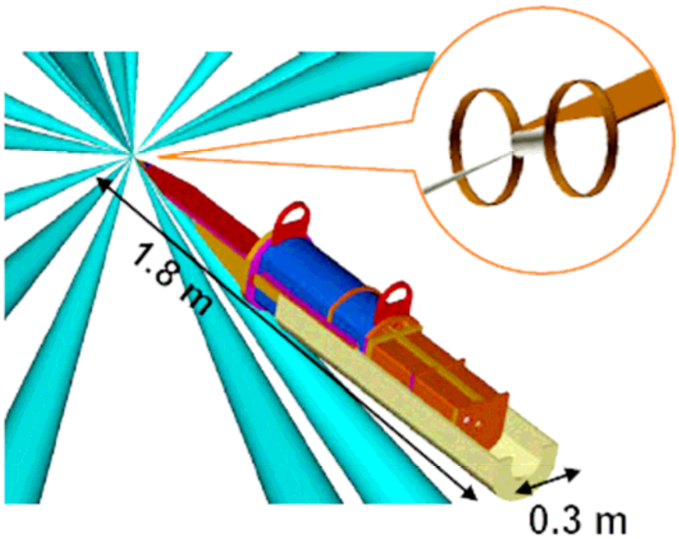


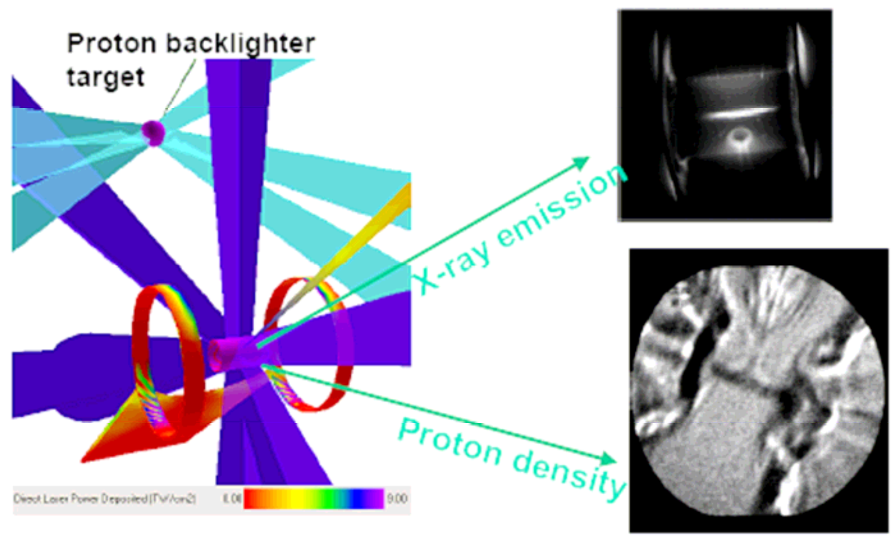
Basic ablative capillary discharge





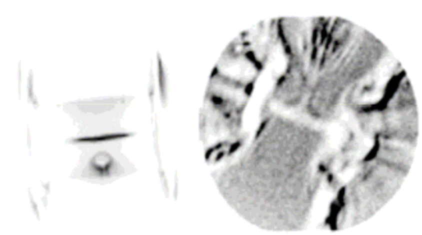
The seed magnetic field is generated in a double coil configuration suitable for OMEGA implosions





Proton deflectrometry technique was developed for detection of the compressed magnetic fields

The 400-ns, 0.1-MG seed magnetic pulse is generated by a compact, 100 Joule device delivering ~80 kA peak coil current.



OFES HEDP Program

	FY 07	FY 08
Heavy Ion Beam	8.03M	8.2M
Fast Ignition	2.8M	2.9M
Magnetized HED plasmas	1.13M	1.18M
Subtotal for Joint Program in HEDLP	11.96M	12.28M
Fusion Science Center in FI	1.1M	1.1M
Magnetized HED Innovative Confinement Concepts (ICC)	3.53M	3.73M

UCRL-PRES-230941

NIF and the National Ignition Campaign

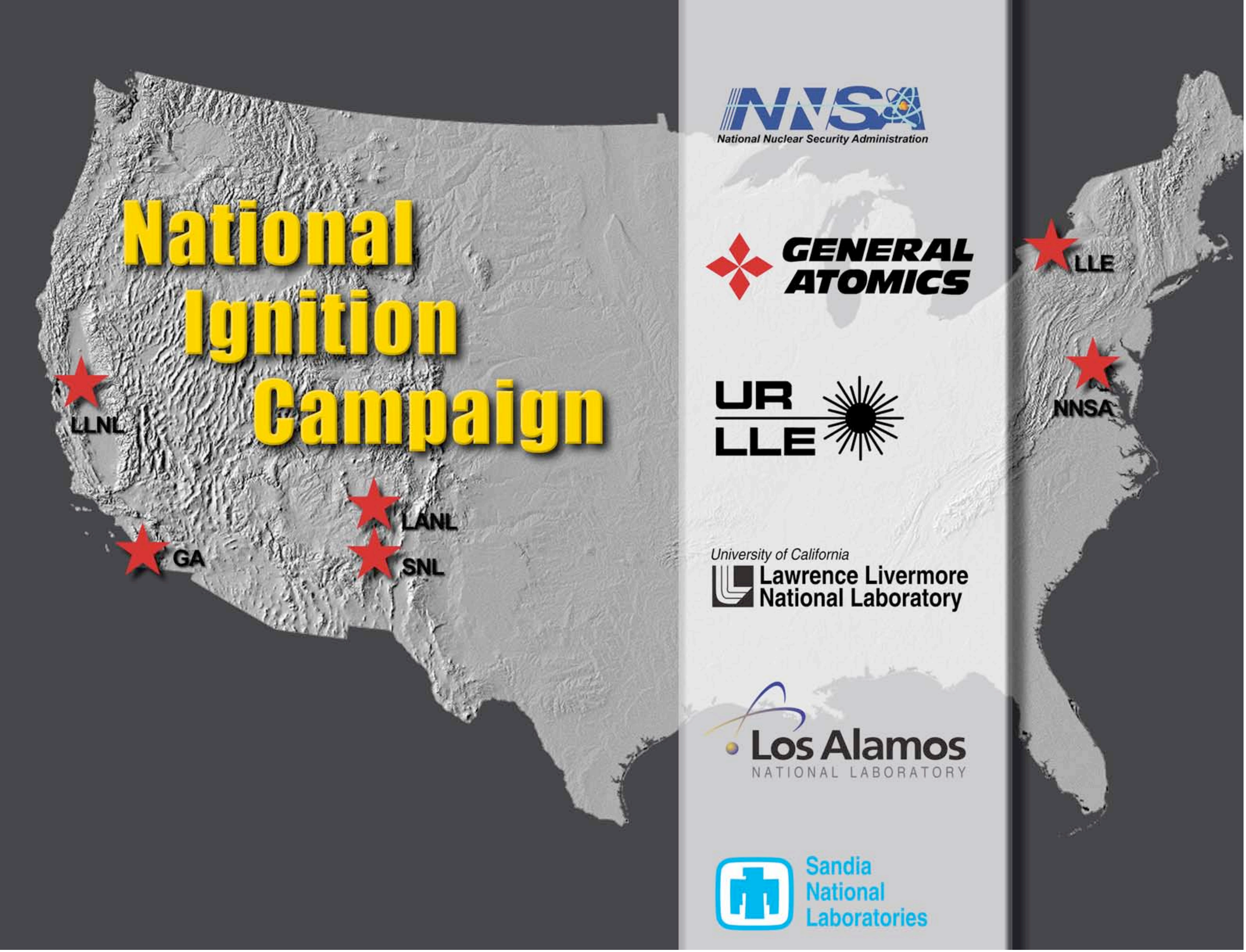
Presentation to
Inaugural IFE Science and Technology Strategic Planning Workshop

NIC

John Lindl
NIF Programs Chief Scientist

April 25, 2007

Work performed under the auspices of the U.S. Department of Energy by
the University of California, Lawrence Livermore National Laboratory under
Contract No. W-7405-ENG-48.


National Ignition Campaign
LLNL
GA
LANL
SNL
LLE
NNSA
NNSA
National Nuclear Security Administration
GENERAL ATOMICS
UR LLE
University of California
Lawrence Livermore National Laboratory
Los Alamos
NATIONAL LABORATORY
Sandia National Laboratories

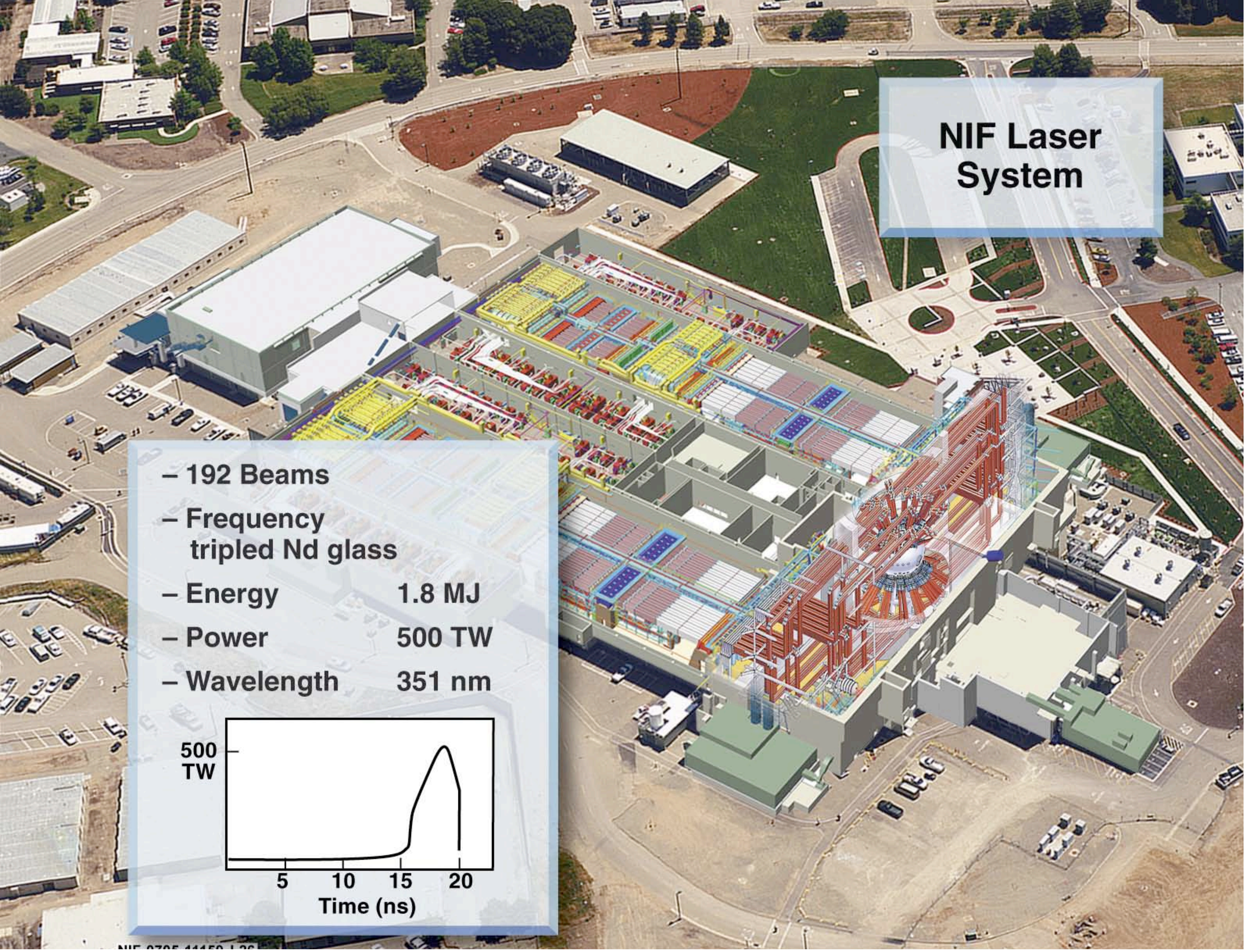
After 15 years, all of the pieces for ignition are almost in place

The National Ignition Campaign

- The NIF laser and the equipment needed for ignition experiments, including high quality targets, will be available in 22 months
- We have an ignition point design target near 1 MJ with a credible chance for ignition during early NIF operations
- The Laser Plasma Interaction (LPI) uncertainty for the first ignition experiments is bounded by ignition designs from about 1-1.3 MJ in laser energy or by a range of hohlraum temperatures from 270-300 eV
- We have an Early Opportunity Shots (EOS) campaign with 96 beams planned to start in 14 months which will allow us to choose the optimum hohlraum temperature and laser energy for initial ignition experiments.
- The initial ignition experiments only scratch the surface of NIF's potential which includes high yields with green light and greatly expanded opportunities for the uses of ignition by decoupling compression and ignition in Fast Ignition (FI).

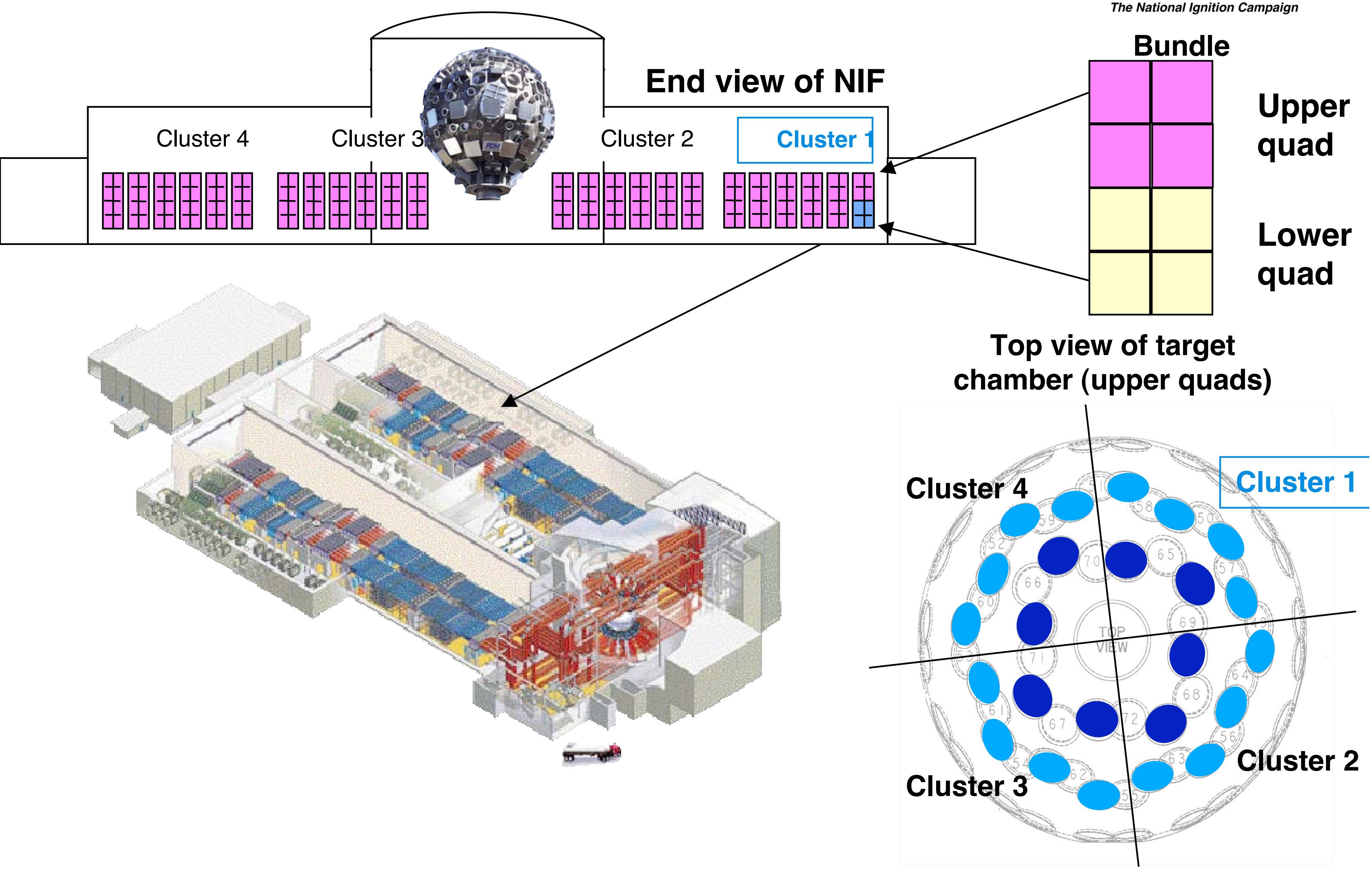

National
Ignition
Facility

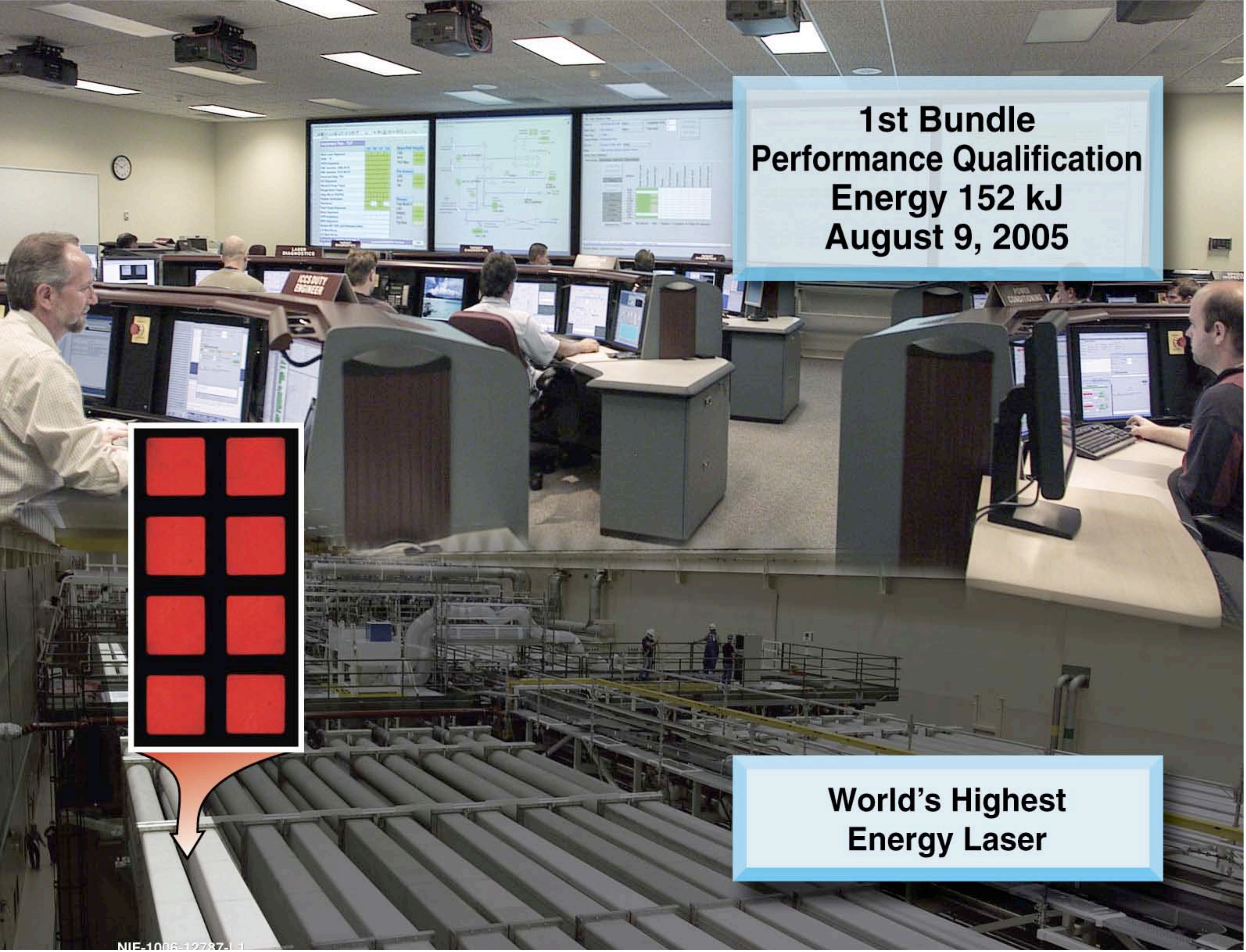

NIF Laser
System

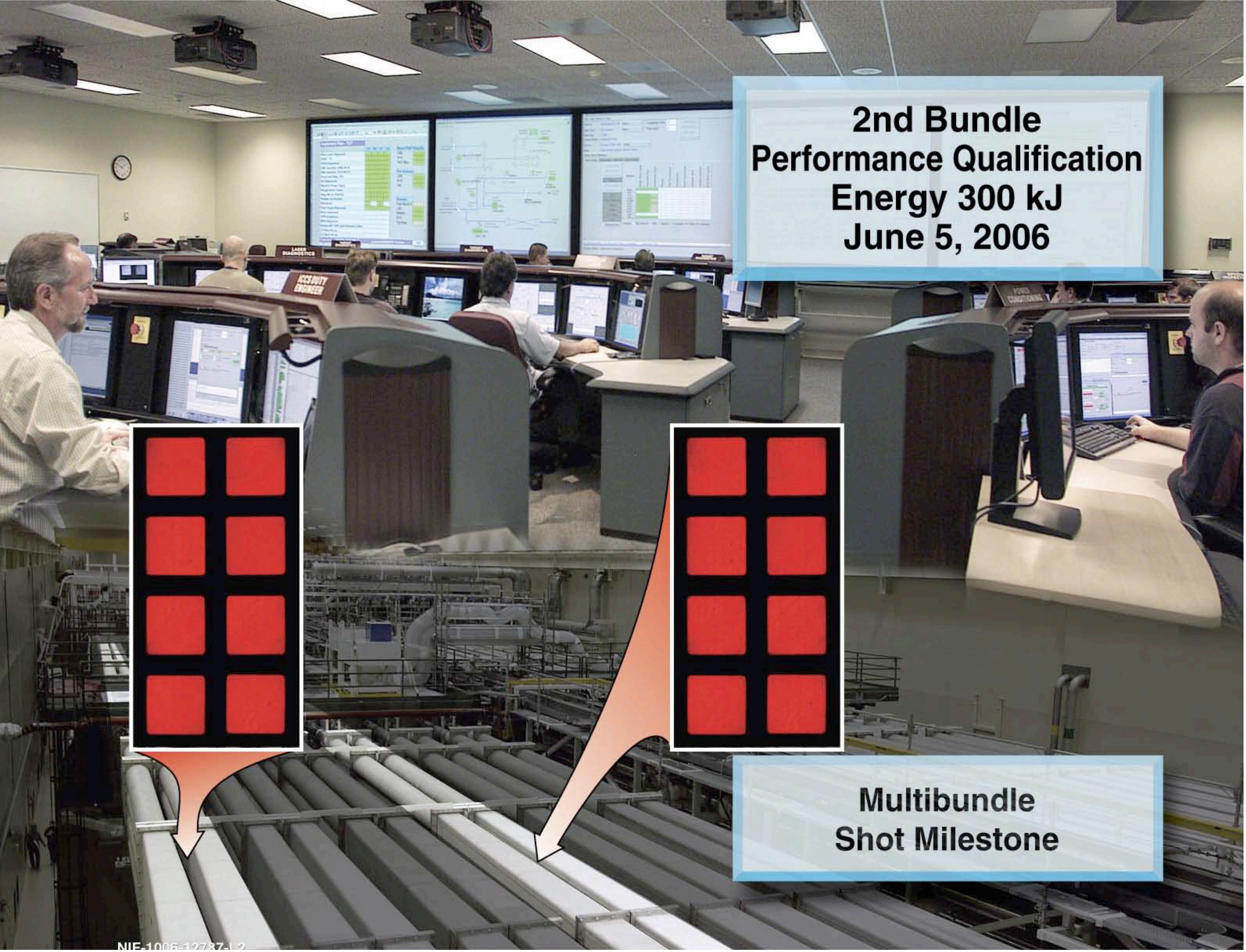

NIF Laser System
– 192 Beams
– Frequency tripled Nd glass
– Energy 1.8 MJ
– Power 500 TW
– Wavelength 351 nm
500 TW
5
10
15
20
Time (ns)

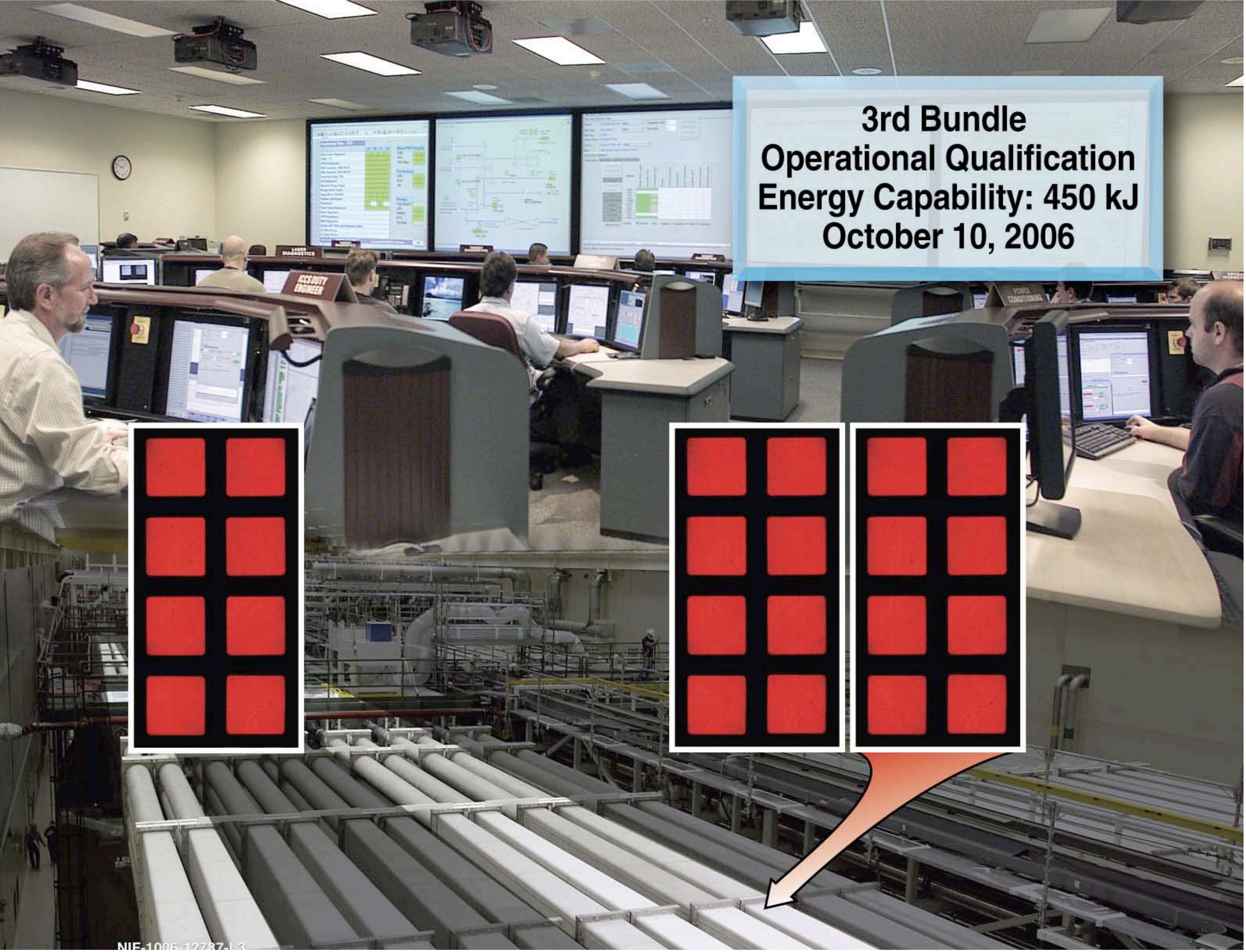
NIF is a 192 beam laser organized into "clusters", "bundles" and "quads"

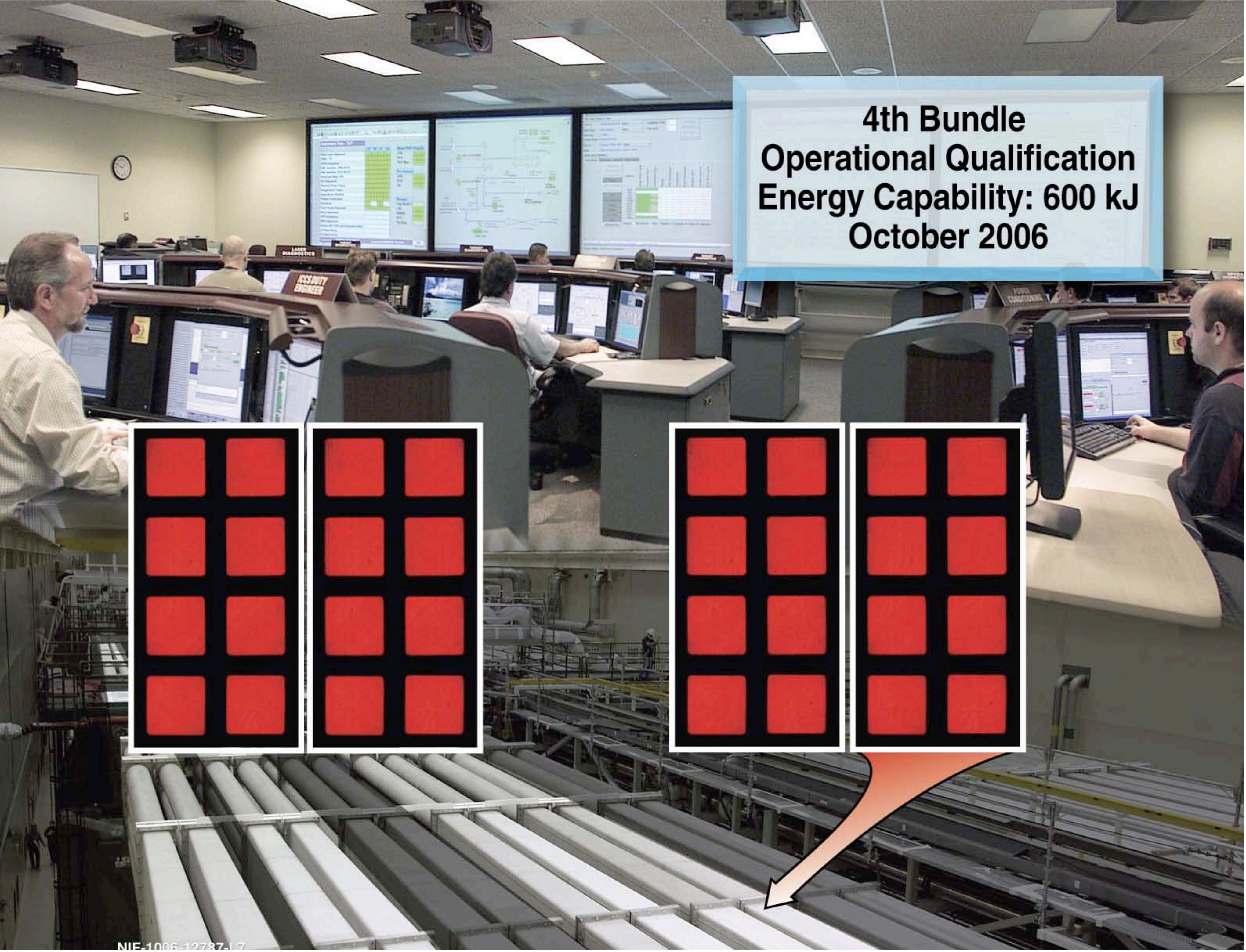
NIC
The National Ignition Campaign



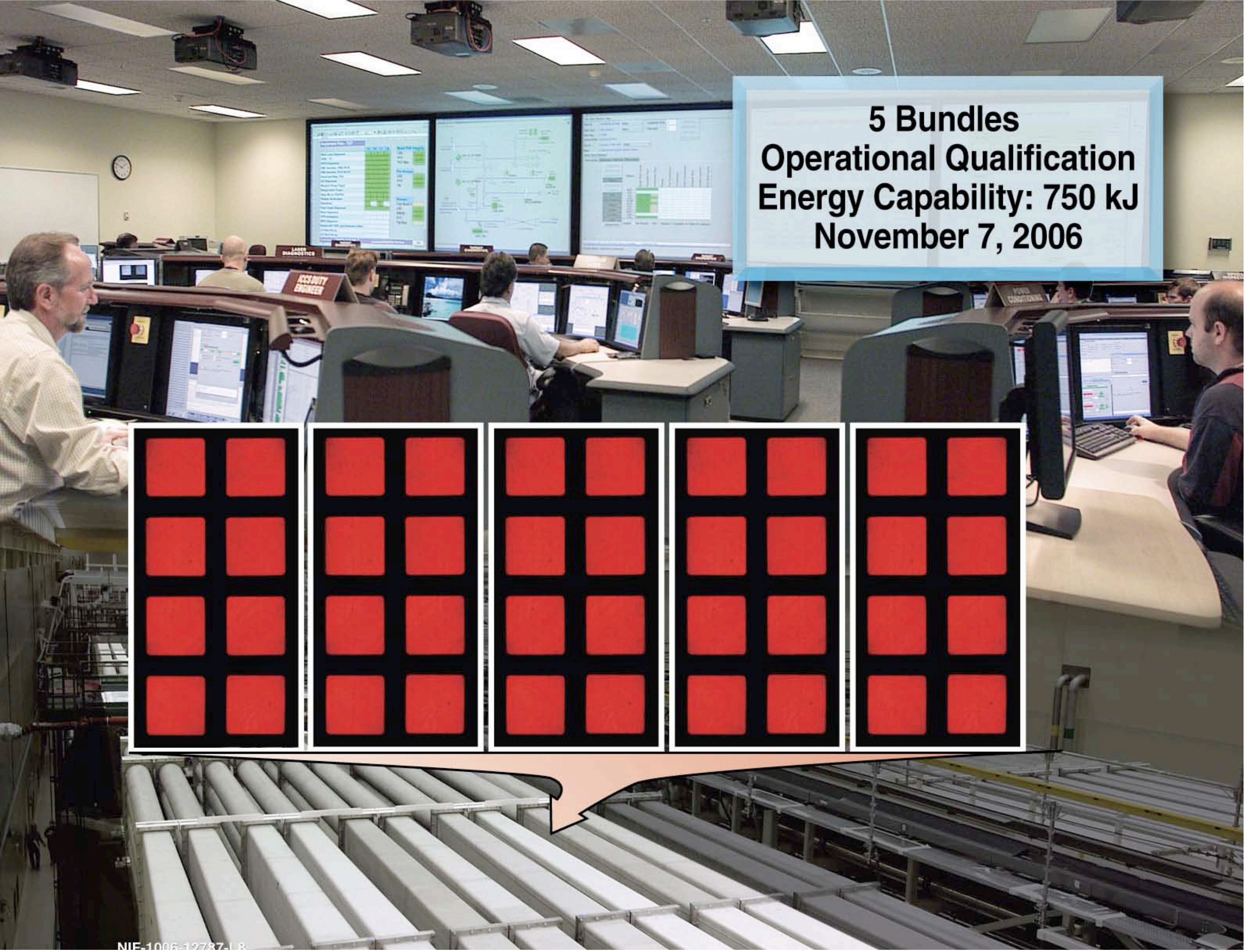

1st Bundle
Performance Qualification
Energy 152 kJ
August 9, 2005
World's Highest
Energy Laser
ICCS DUTY ENGINEER
LASER DIAGNOSTICS
NIF-1006-12787-L1


2nd Bundle
Performance Qualification
Energy 300 kJ
June 5, 2006
ICCS DUTY ENGINEER
Multibundle
Shot Milestone
NIF-1006-12787-L2

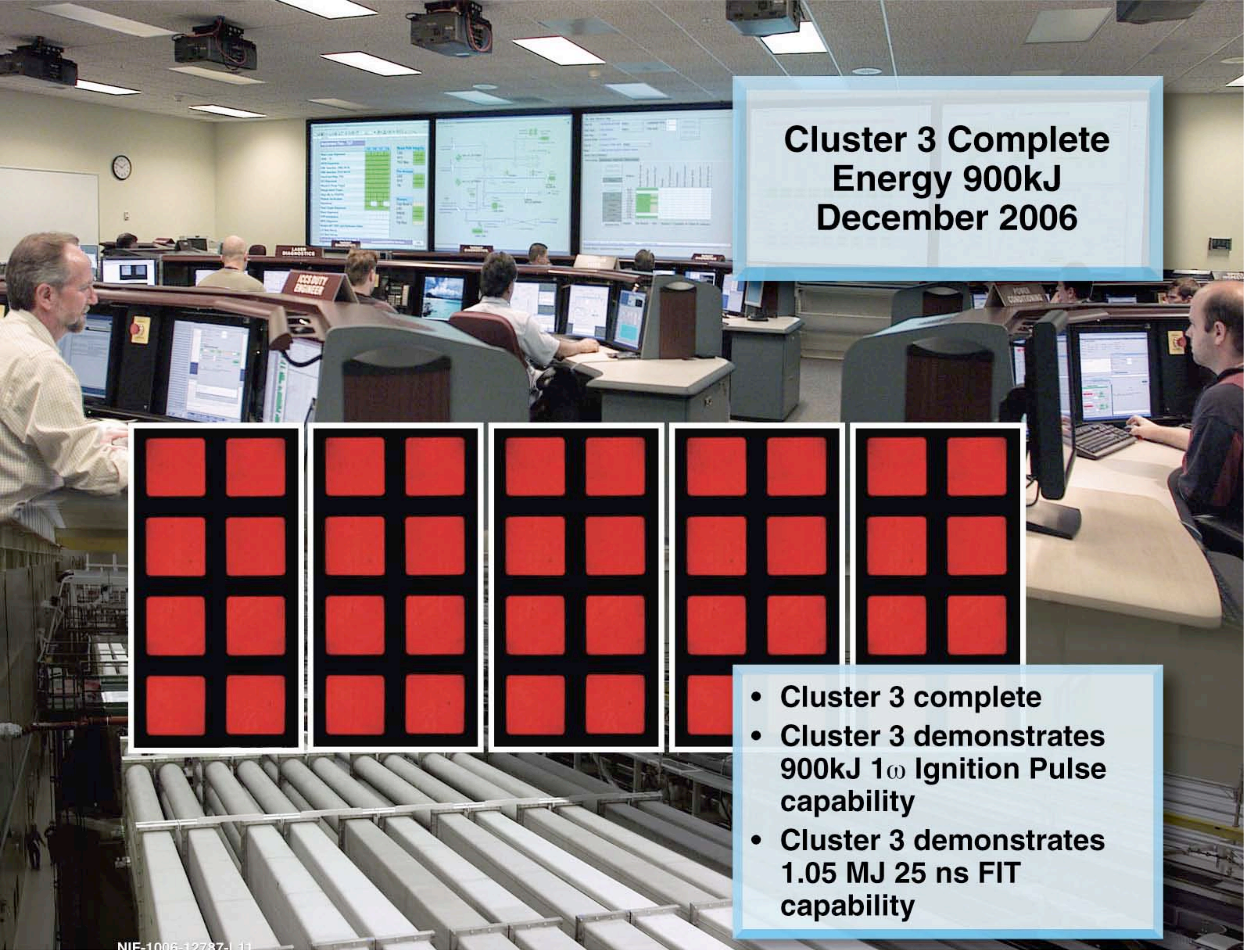

3rd Bundle
Operational Qualification
Energy Capability: 450 kJ
October 10, 2006
ICCS DUTY ENGINEER
NIF-1006-12787-L3



4th Bundle
Operational Qualification
Energy Capability: 600 kJ
October 2006
ICCS DUTY ENGINEER
LASER DIAGNOSTICS
NIF-1006-12787-L7

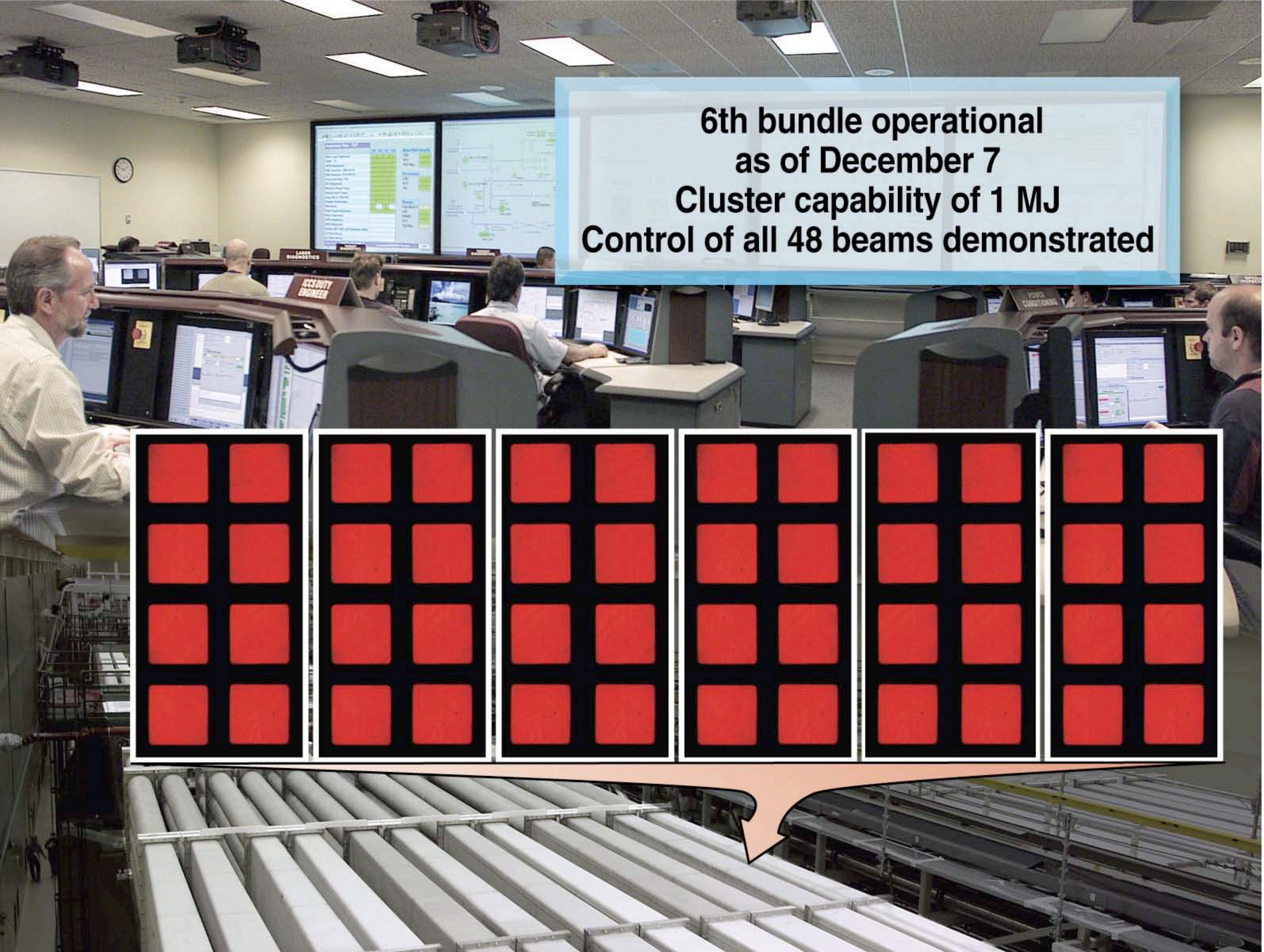


NIF-1006-12787-L8

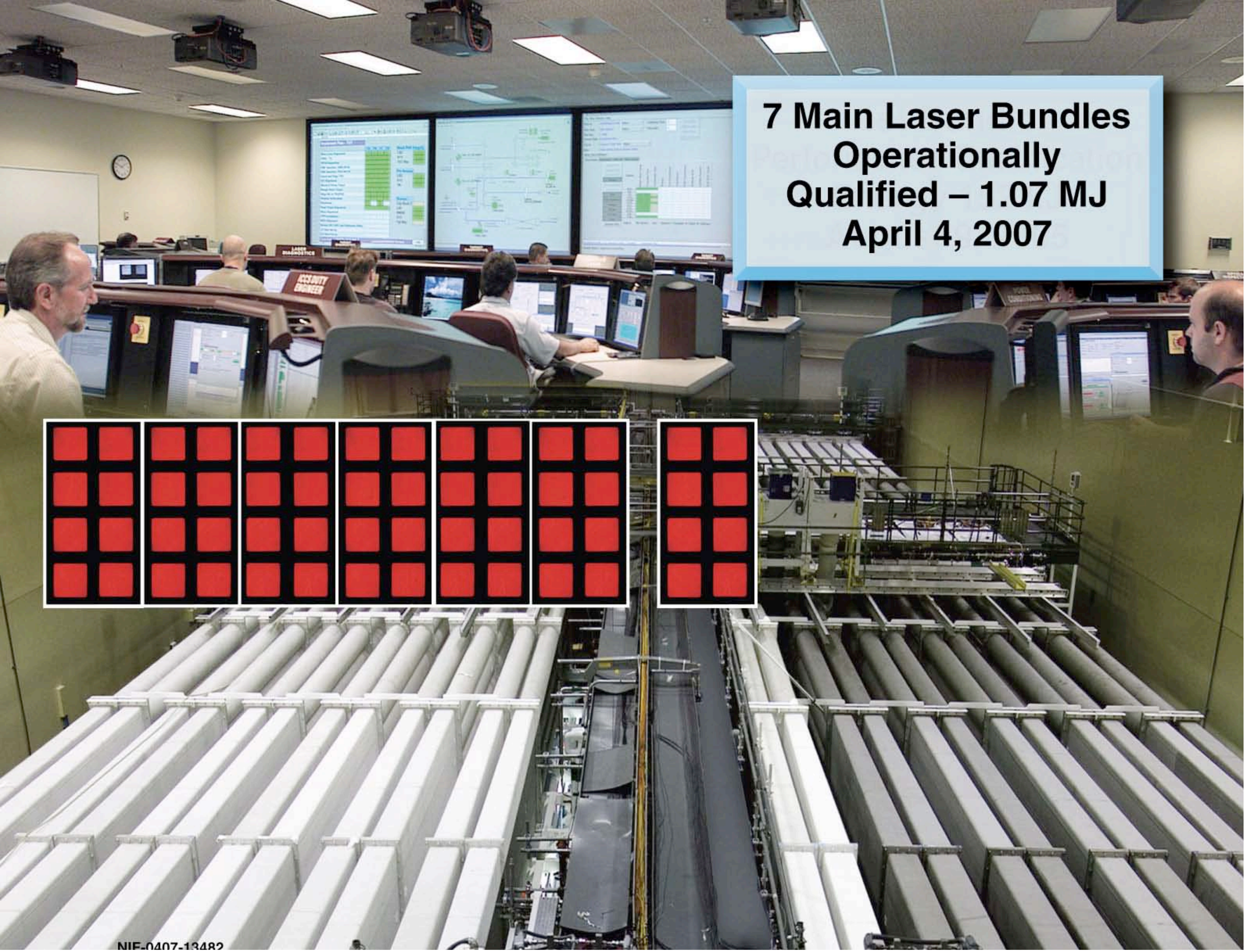


Cluster 3 Complete
Energy 900kJ
December 2006

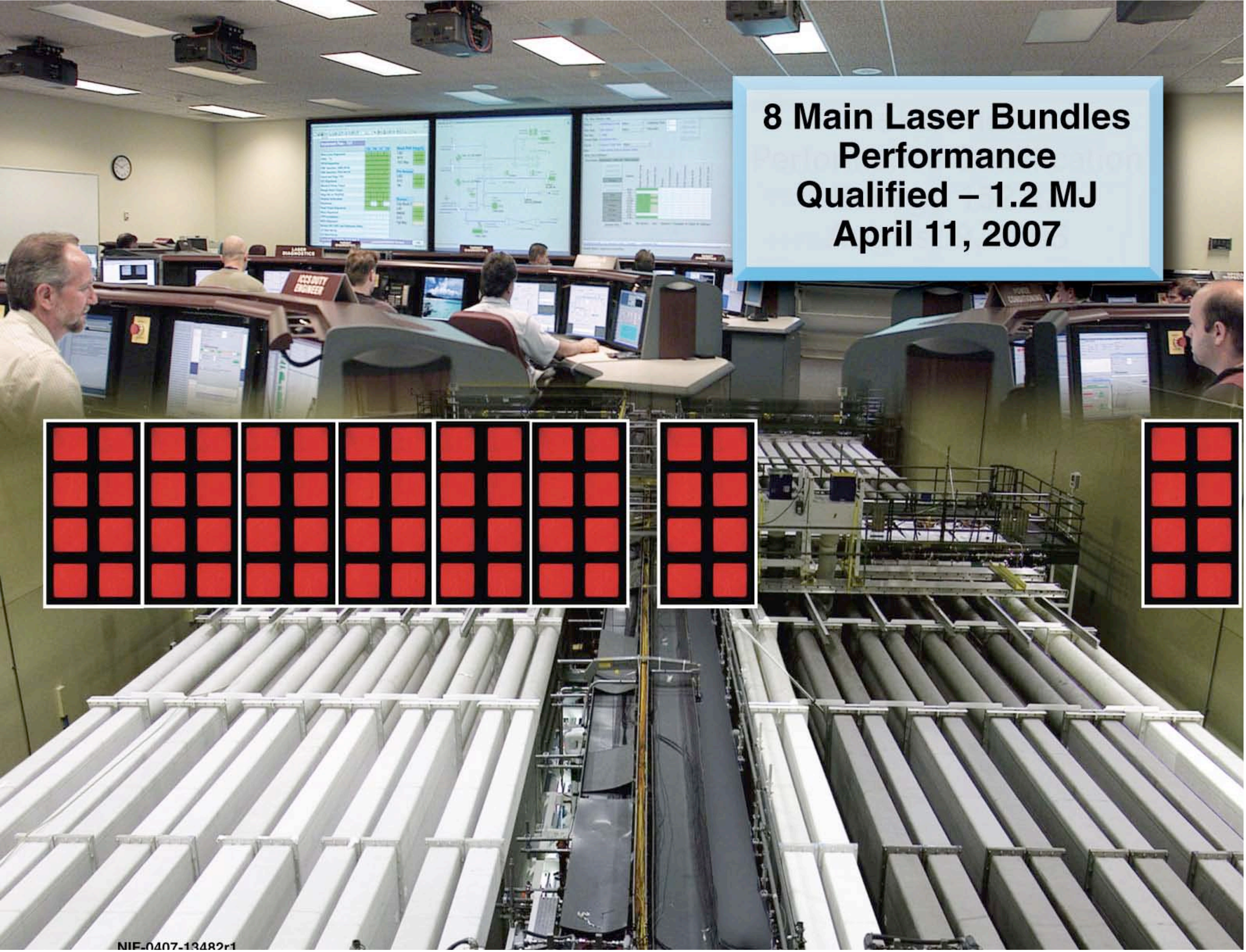
- Cluster 3 complete
- Cluster 3 demonstrates 900kJ 1ω Ignition Pulse capability
- Cluster 3 demonstrates 1.05 MJ 25 ns FIT capability



NIF-1006-12787-L10



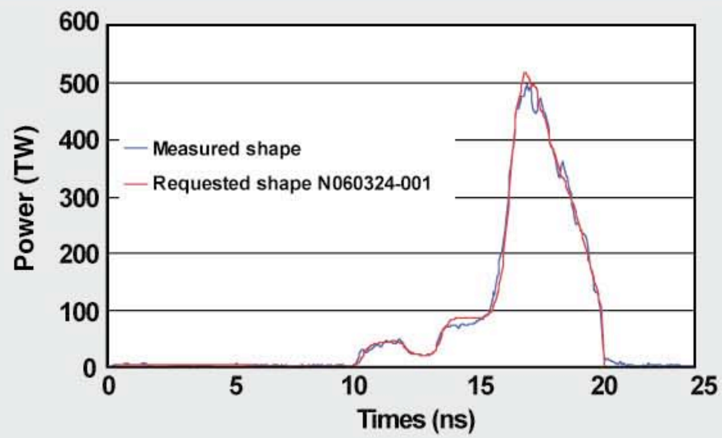
NIF-0407-13482


8 Main Laser Bundles
Performance
Qualified – 1.2 MJ
April 11, 2007
NIF-0407-13482r1

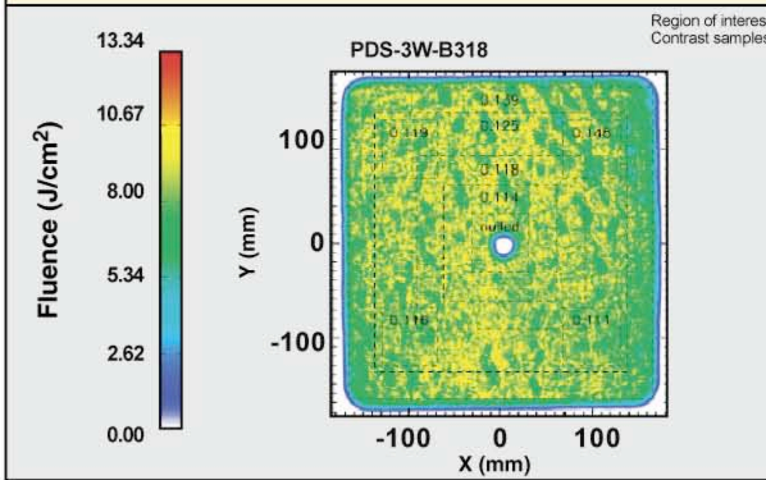
1.8 MJ NIC ignition point design, energy, power, pulse shape & beam smoothing were achieved simultaneously (single beam)

NIC
The National Ignition Campaign

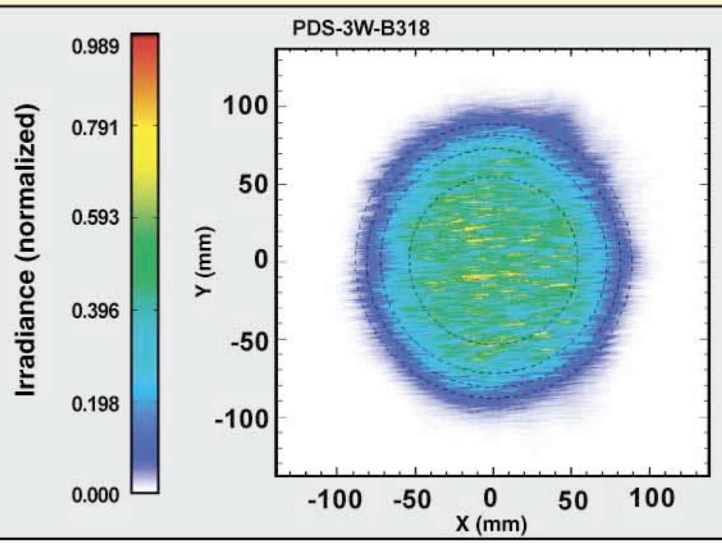
3ω Pulse Shape (500 TW)



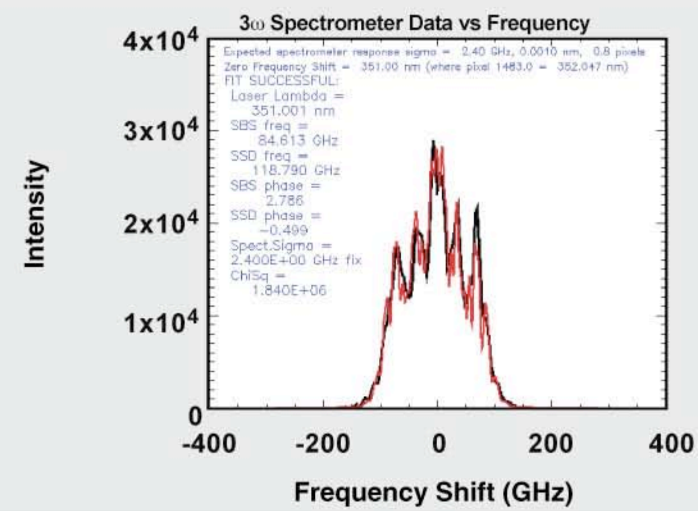
3ω Field Profile (CR = 12.5%)



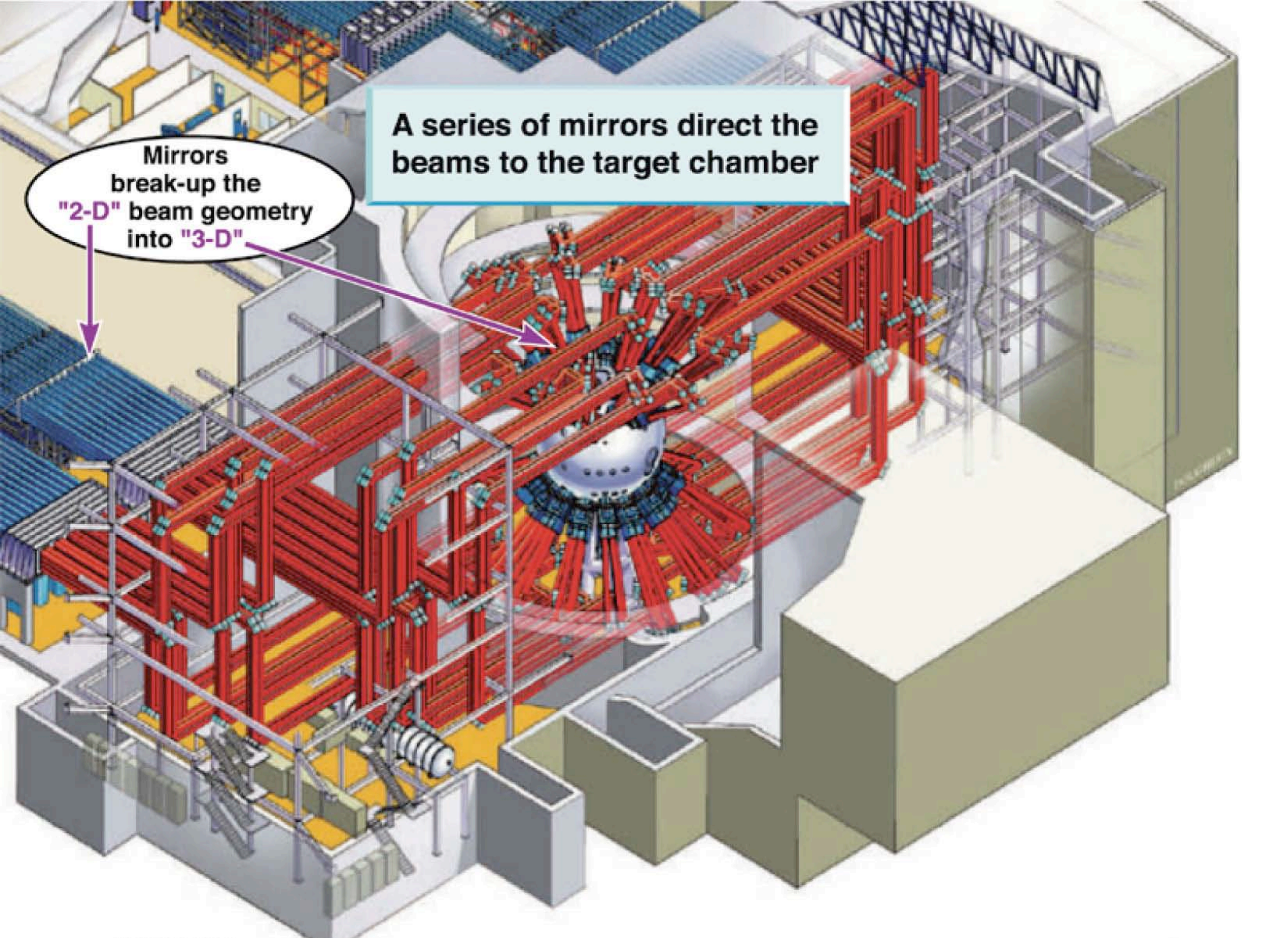
3ω Focal Spot (1.3 × 1.2 mm²)



3ω SSD Bandwidth (100GHz)



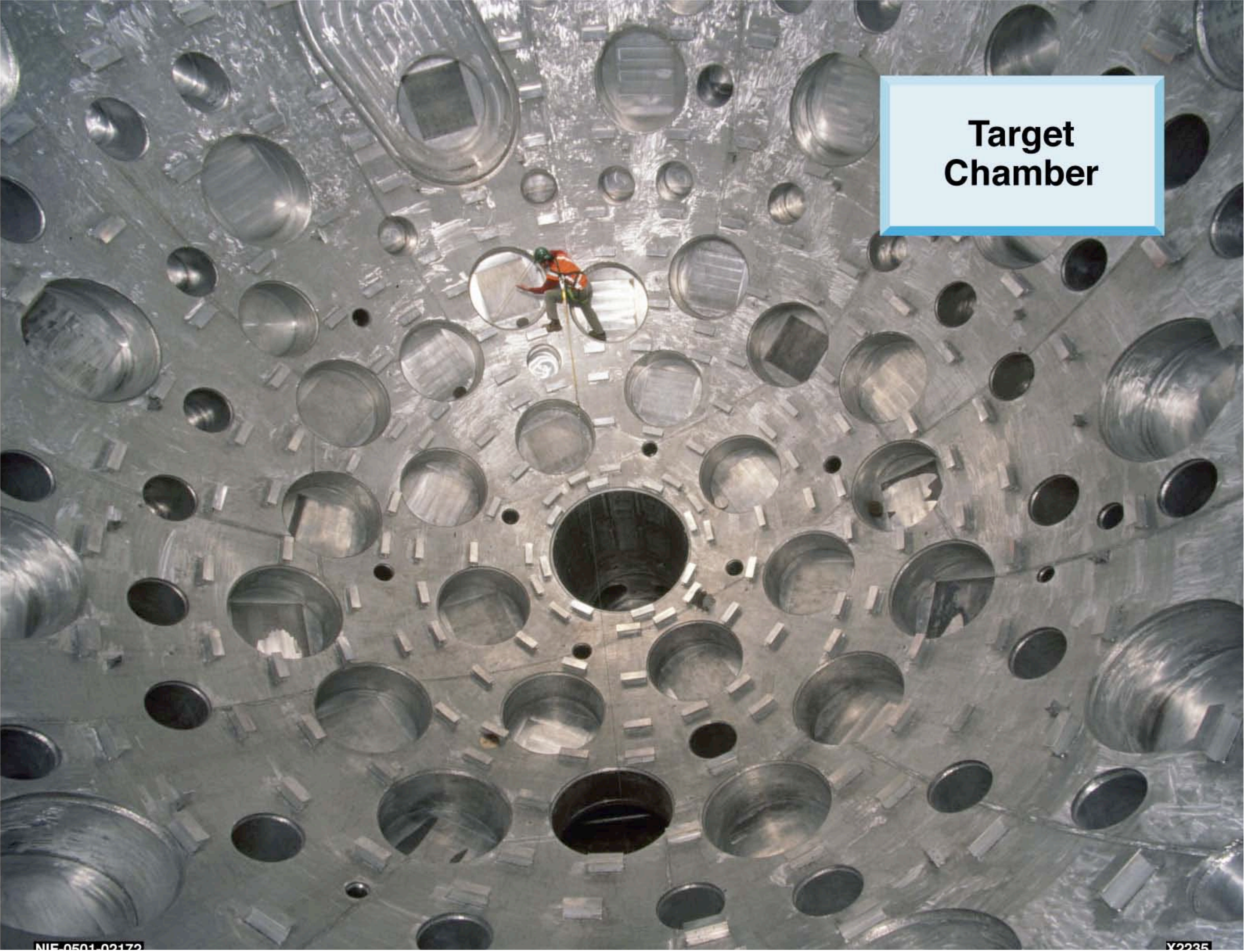
NIF-0506-11982

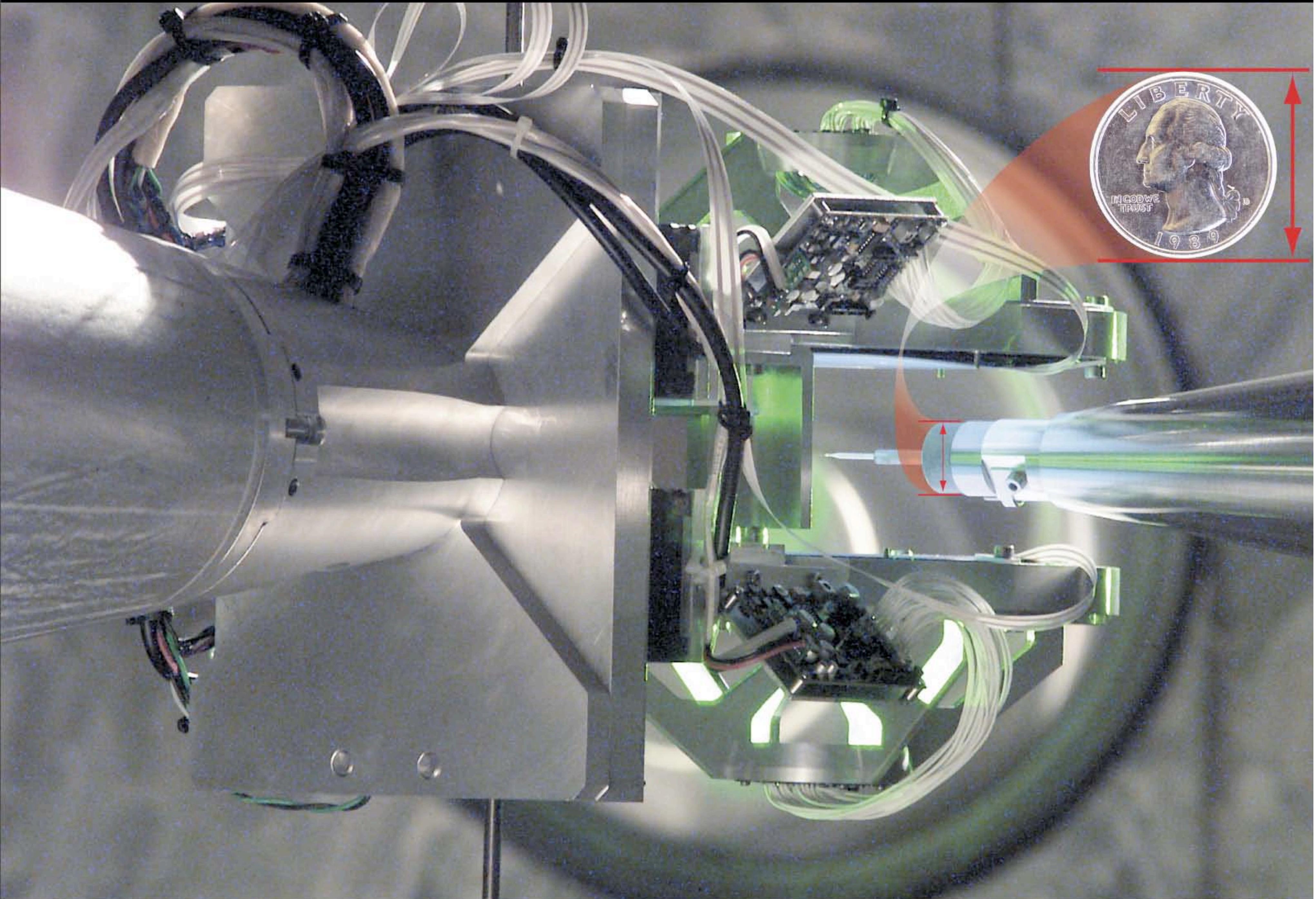


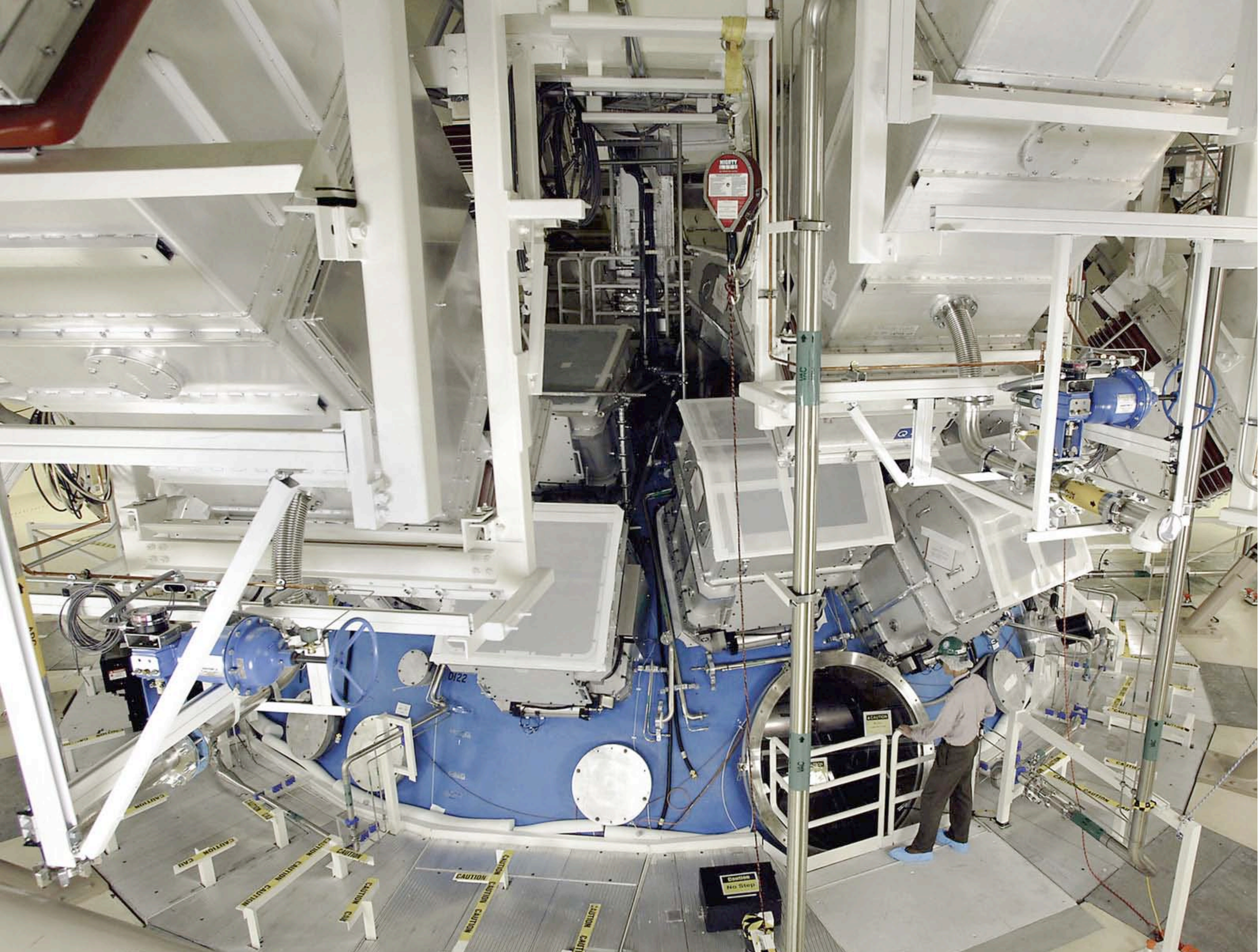
NIF-0604-09073L2

R0033


Target
Chamber
NIF-0105-10124
P8136

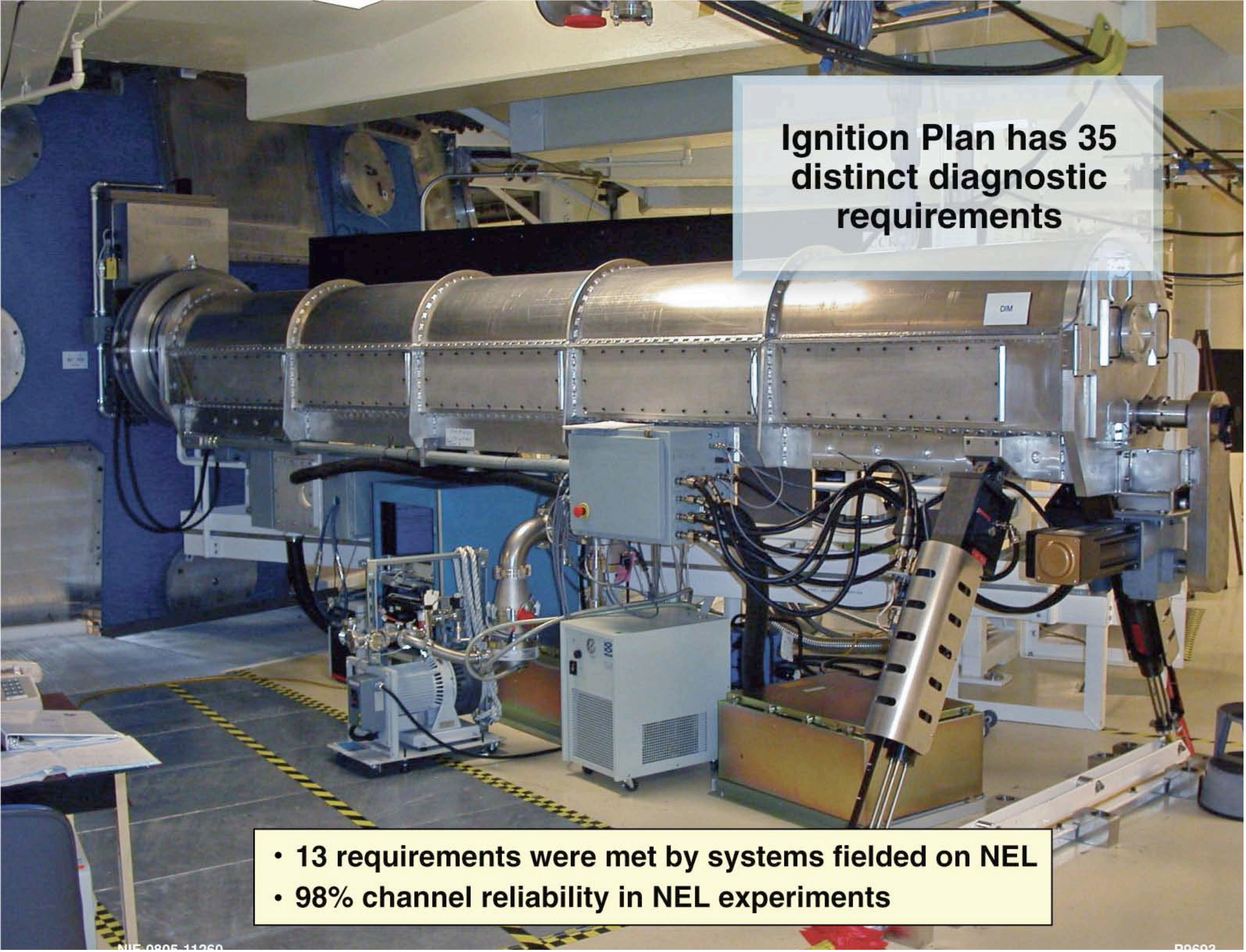

Target
Chamber
NIF-0501-02172
X2235


LIBERTY
IN GOD WE TRUST
1989



NIF-0406-11882

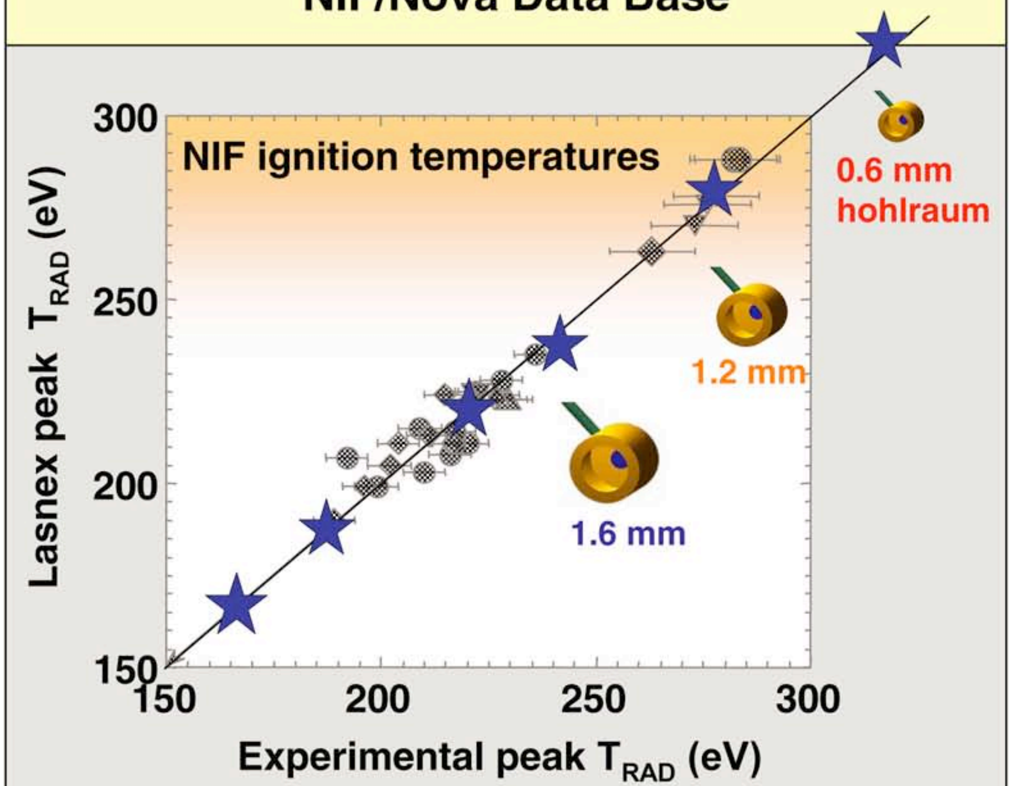
P0196


Ignition Plan has 35 distinct diagnostic requirements
DIM
• 13 requirements were met by systems fielded on NEL
• 98% channel reliability in NEL experiments

Our first hohlraum experiments on NIF have measured drive beyond the Nova data base (exceeding 300 eV)

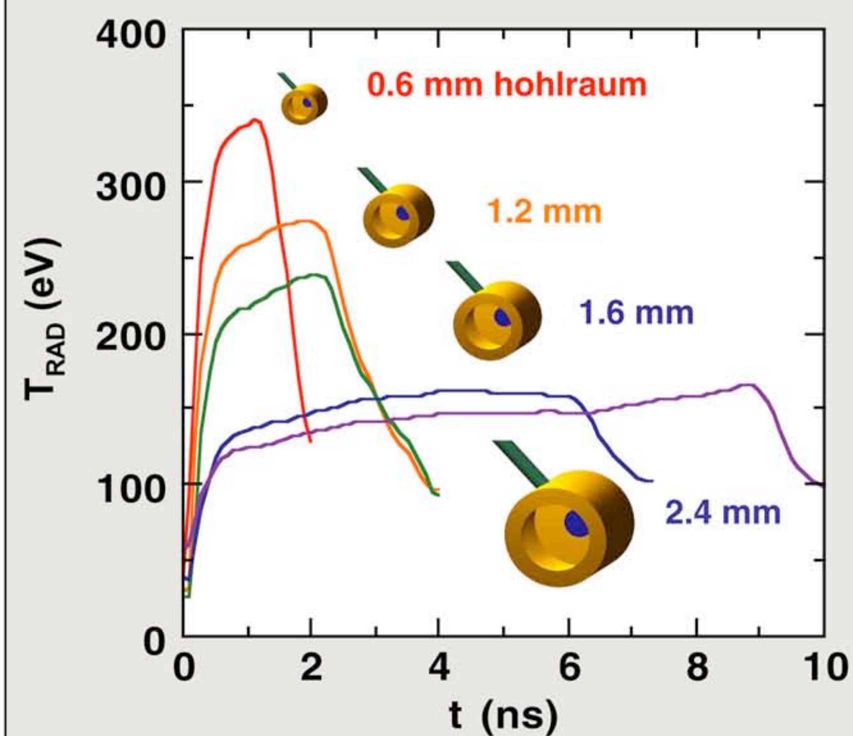
The National Ignition Facility

NIF/Nova Data Base



NIF experiments follow hohlraum drive scaling

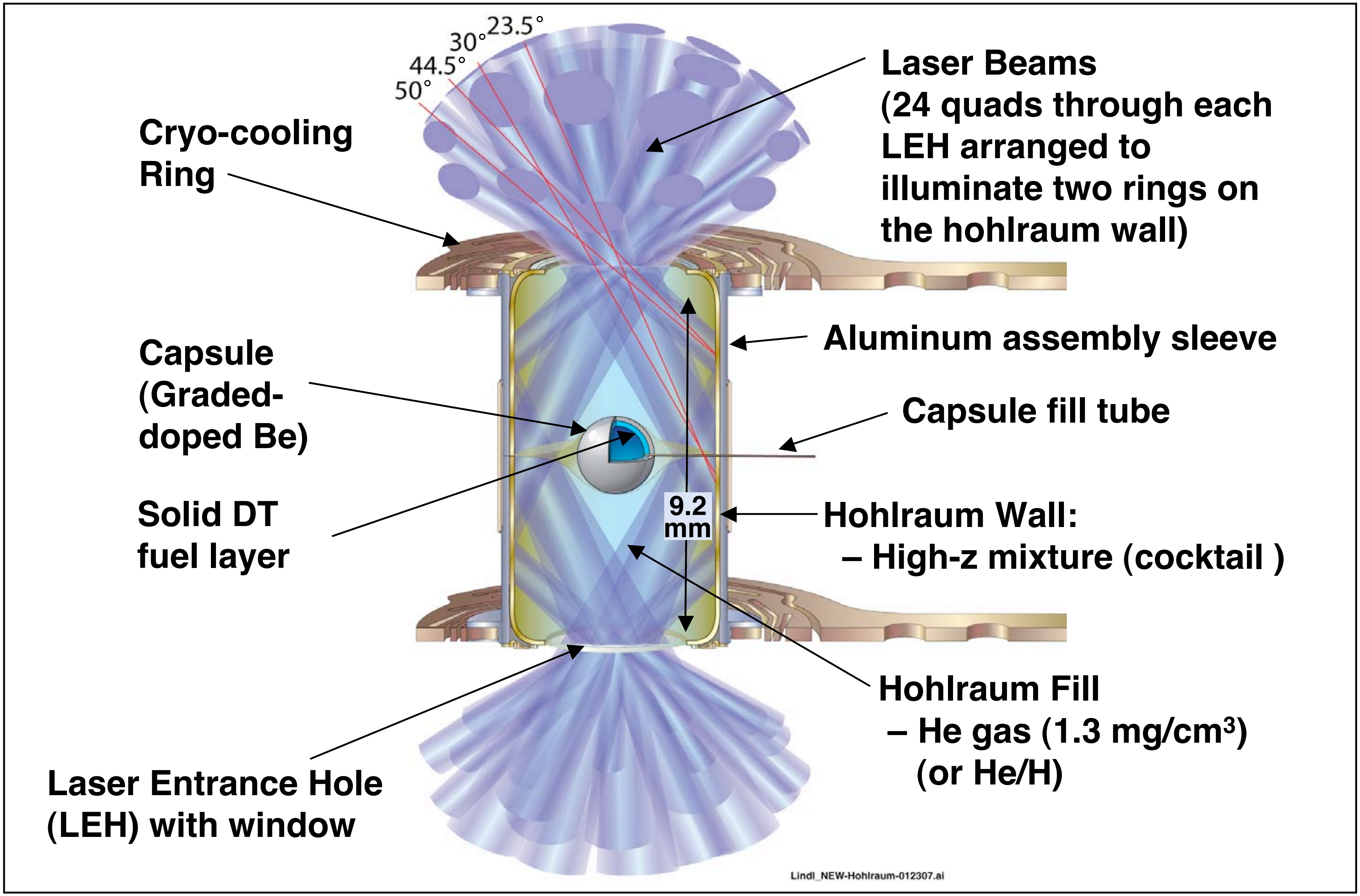
Hohlraum T_{RAD} vs Time



NIF experiments have explored new drive regimes

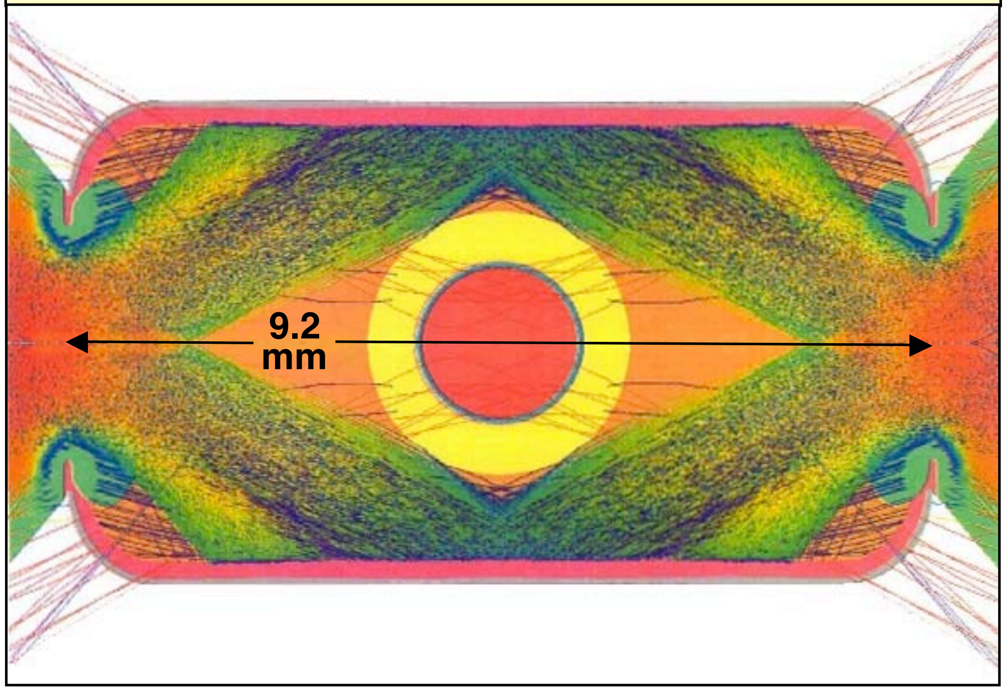
The NIF point design has a graded-doped, beryllium capsule in a $U_{0.75}Au_{.25}$ hohlraum driven at 300 eV

NIC
The National Ignition Campaign

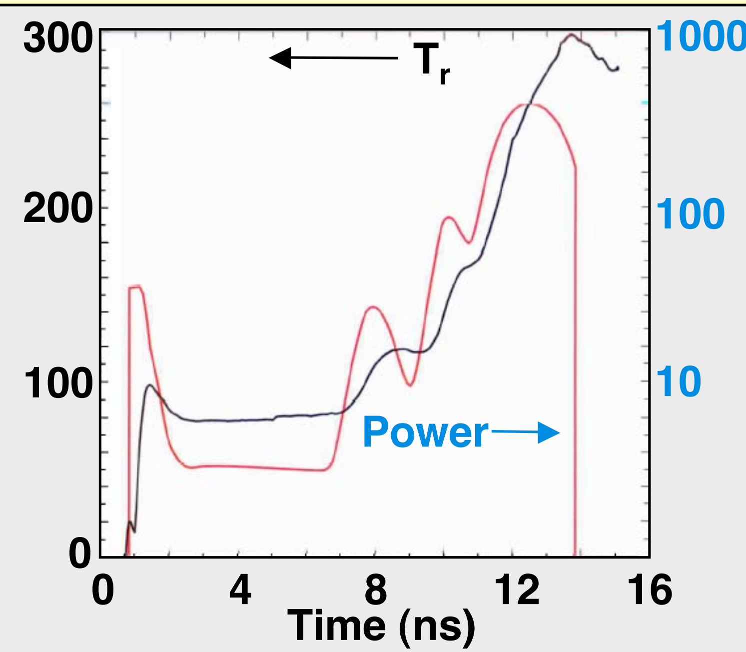


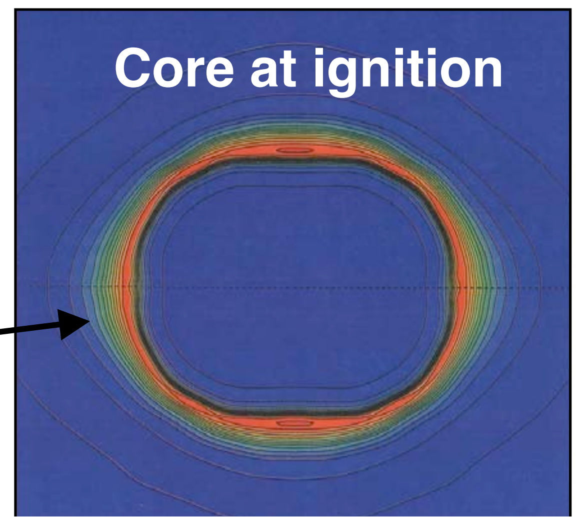
Optimized Lasnex 2D symmetry calculations meet the point design requirements

Beam spots are as large as possible consistent with LEH clipping and symmetry control



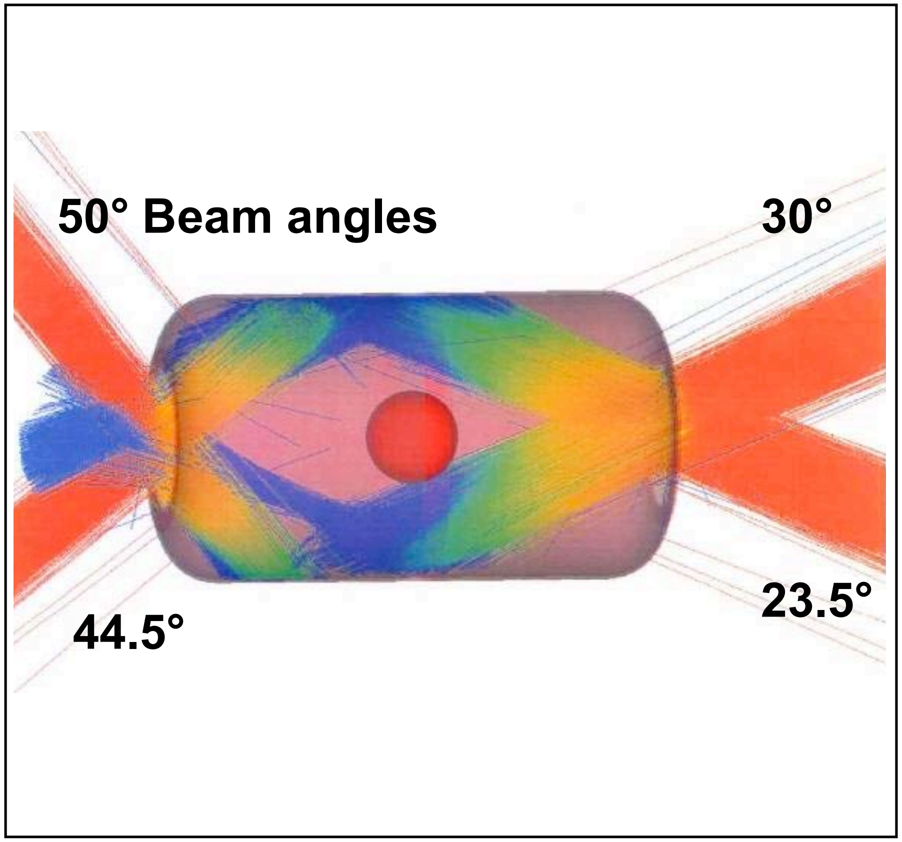
Power (TW) and T_r (eV)



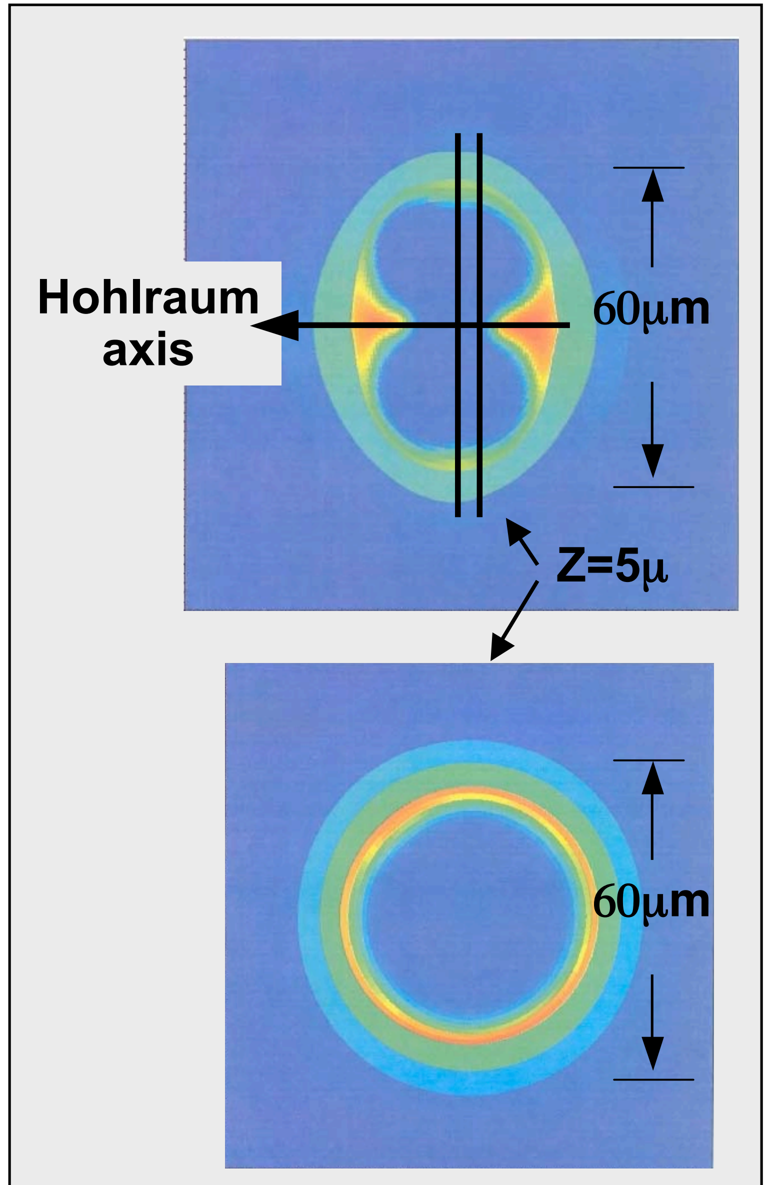


The imploded fuel core shows very little residual angular variation from the NIF multi-cone geometry

Initial calculations with Hydra of the 300 eV point design show very little 3D azimuthal asymmetry



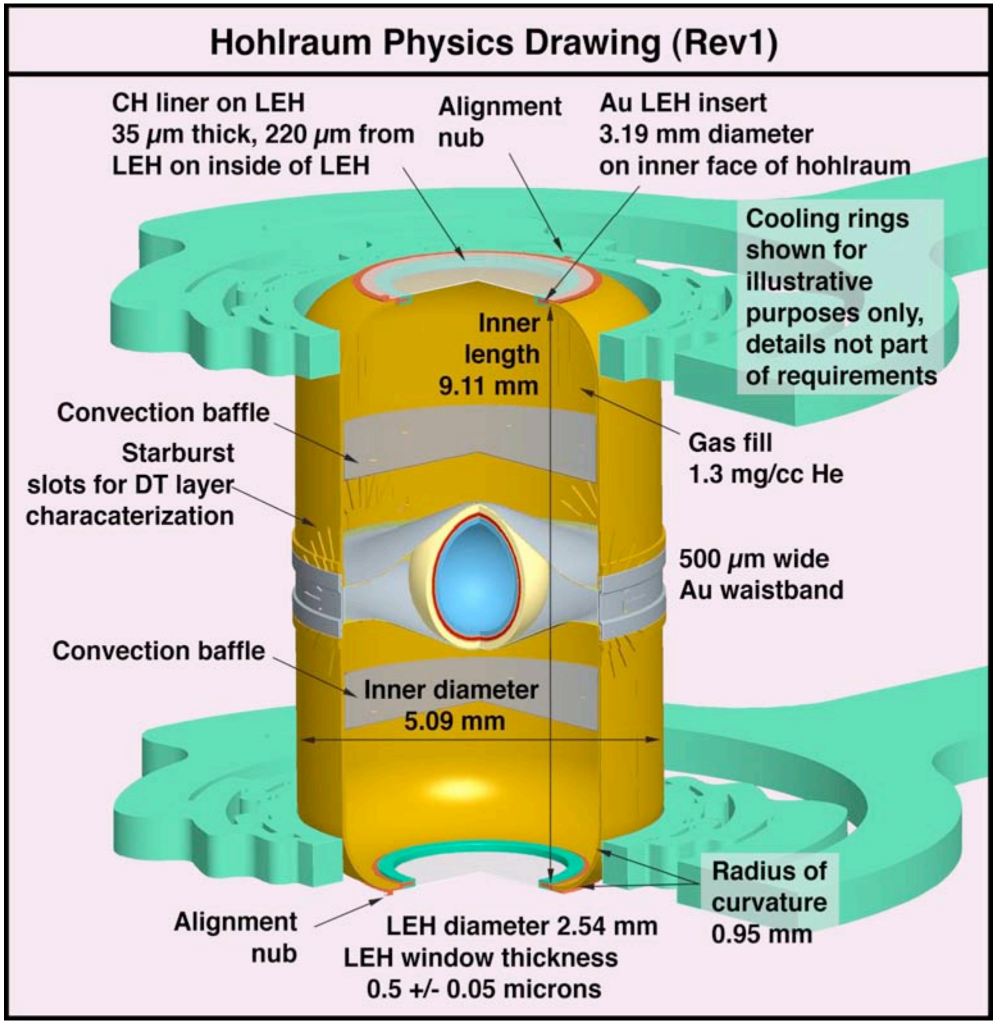
- The 2D implosion had not been optimized for this 3D implosion
- We will soon be doing 3D calculations to assess the impact of power balance and pointing errors

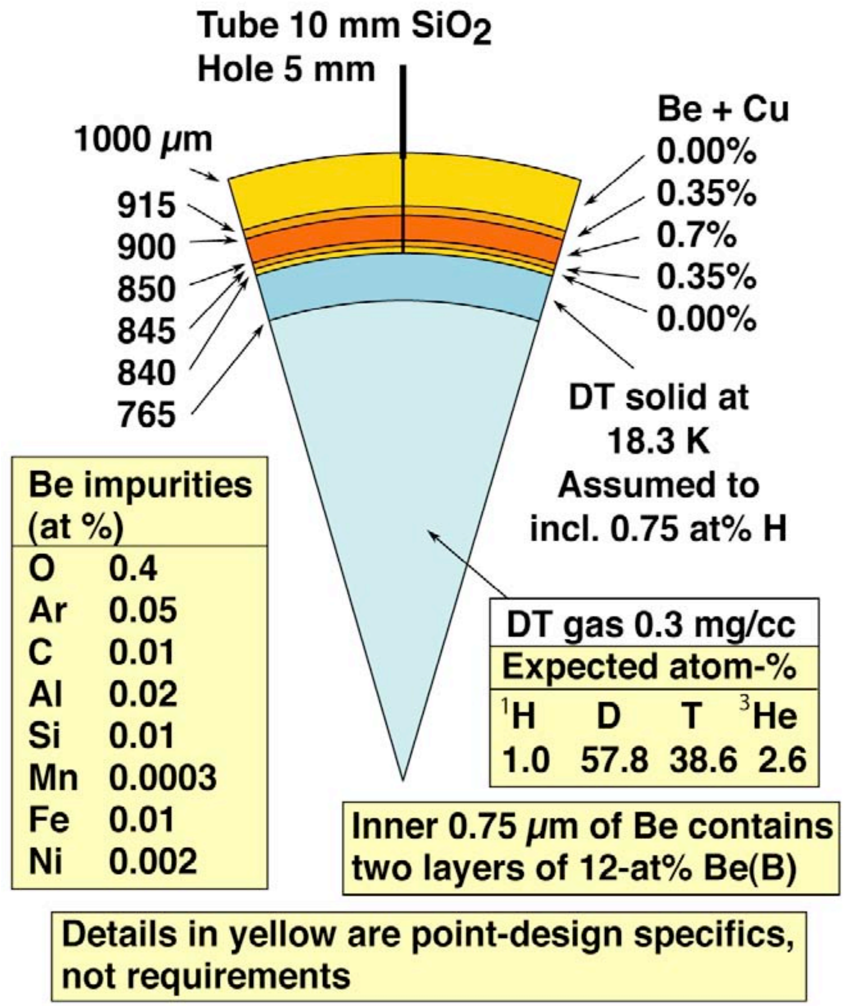


Cross section perpendicular to the hohlraum axis

We have a point design for ignition that is under configuration control by the National Ignition Campaign(NIC) program

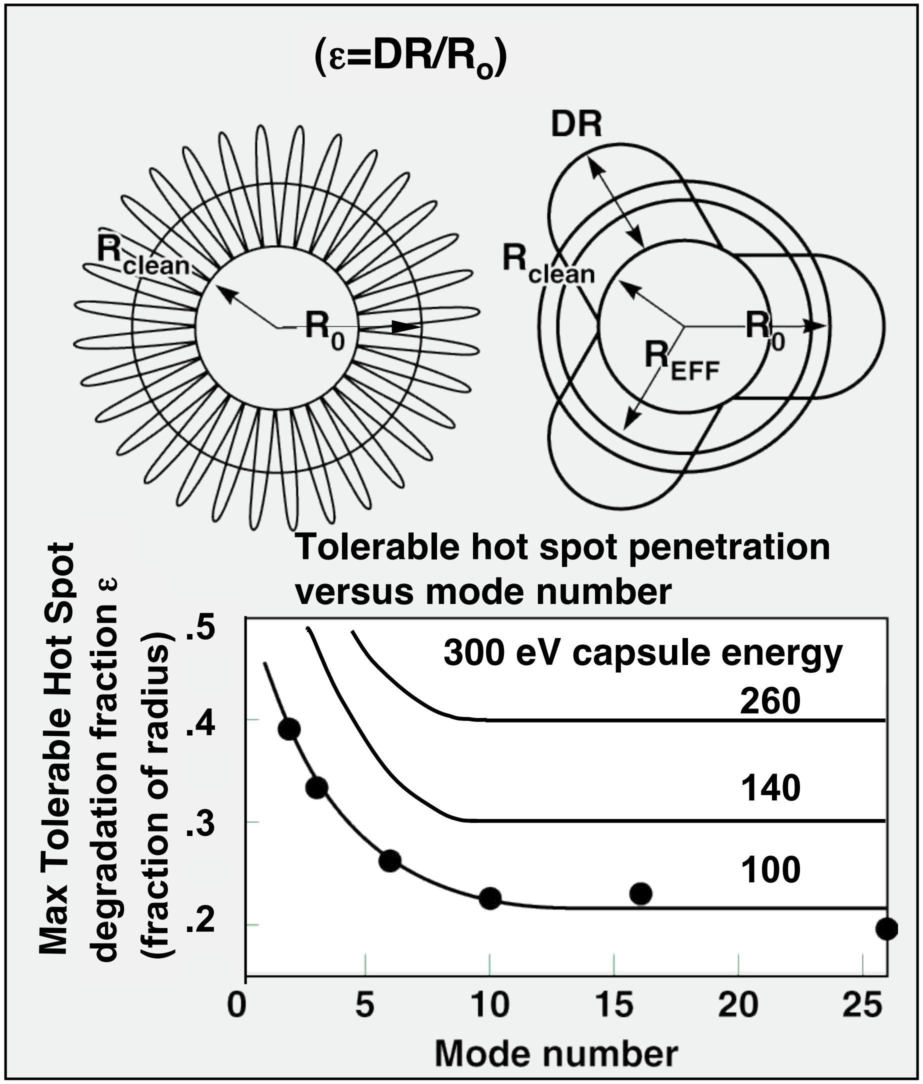
NIC
The National Ignition Campaign





The impact of most 3D effects that degrade an implosion can be specified as a hot spot degradation fraction

The National Ignition Campaign



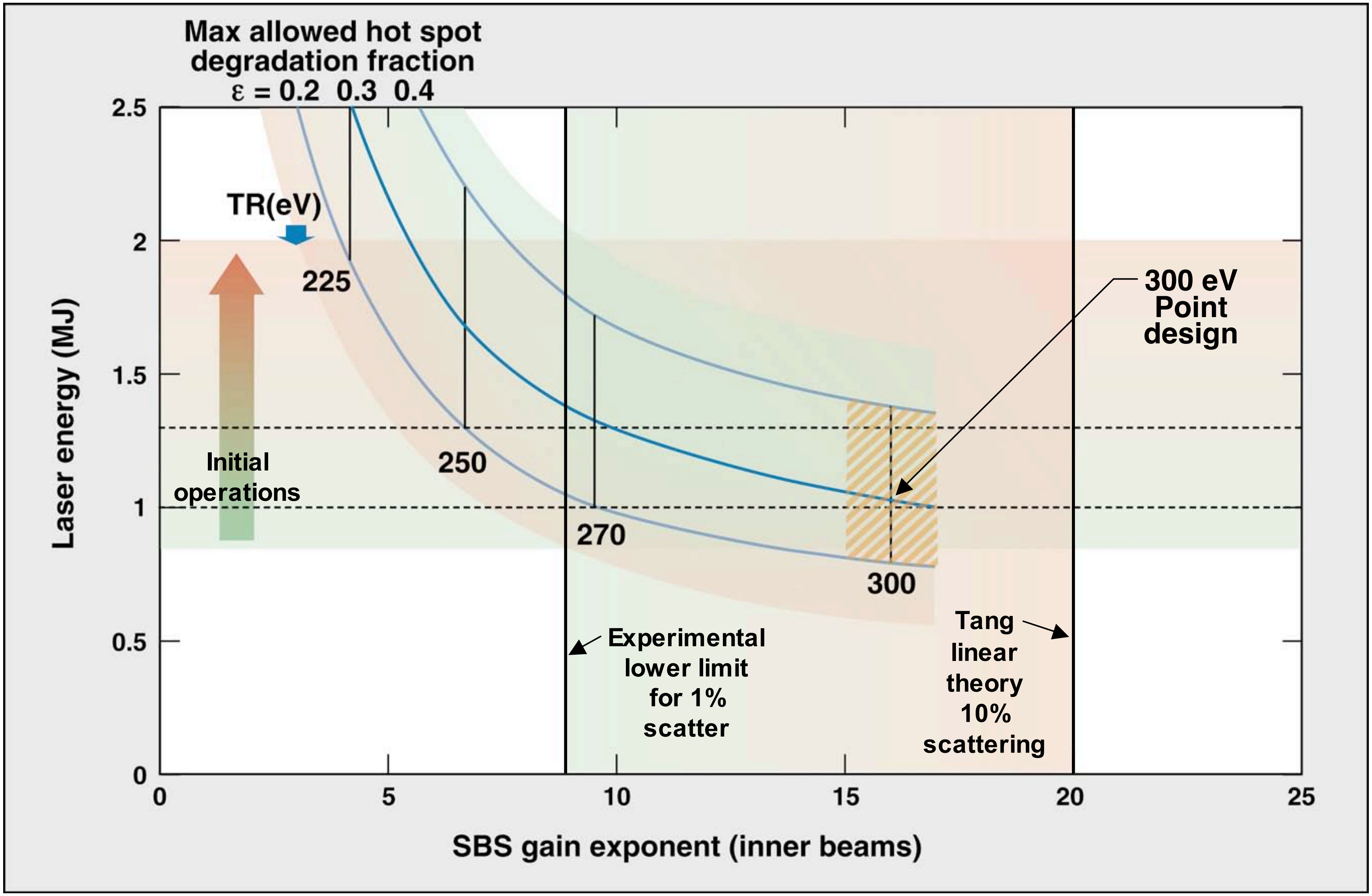
R. Kishony and D. Shvarts Phys. Plasmas **8** (2001) 4925

- Low spatial frequency Perturbations
  - Hohlraum asymmetry
  - Pointing errors
  - Power Imbalance
  - Capsule misplacement in chambe
- High spatial frequency Perturbations
  - DT ice roughness
  - Ablator roughness
  - Ablator microstructure

- The hot spot penetration is the fraction of the hot spot radius perturbed by the various sources of error
- The specifications developed for NIF ignition designs result in a hot spot penetration of ~20% for short wavelength modes

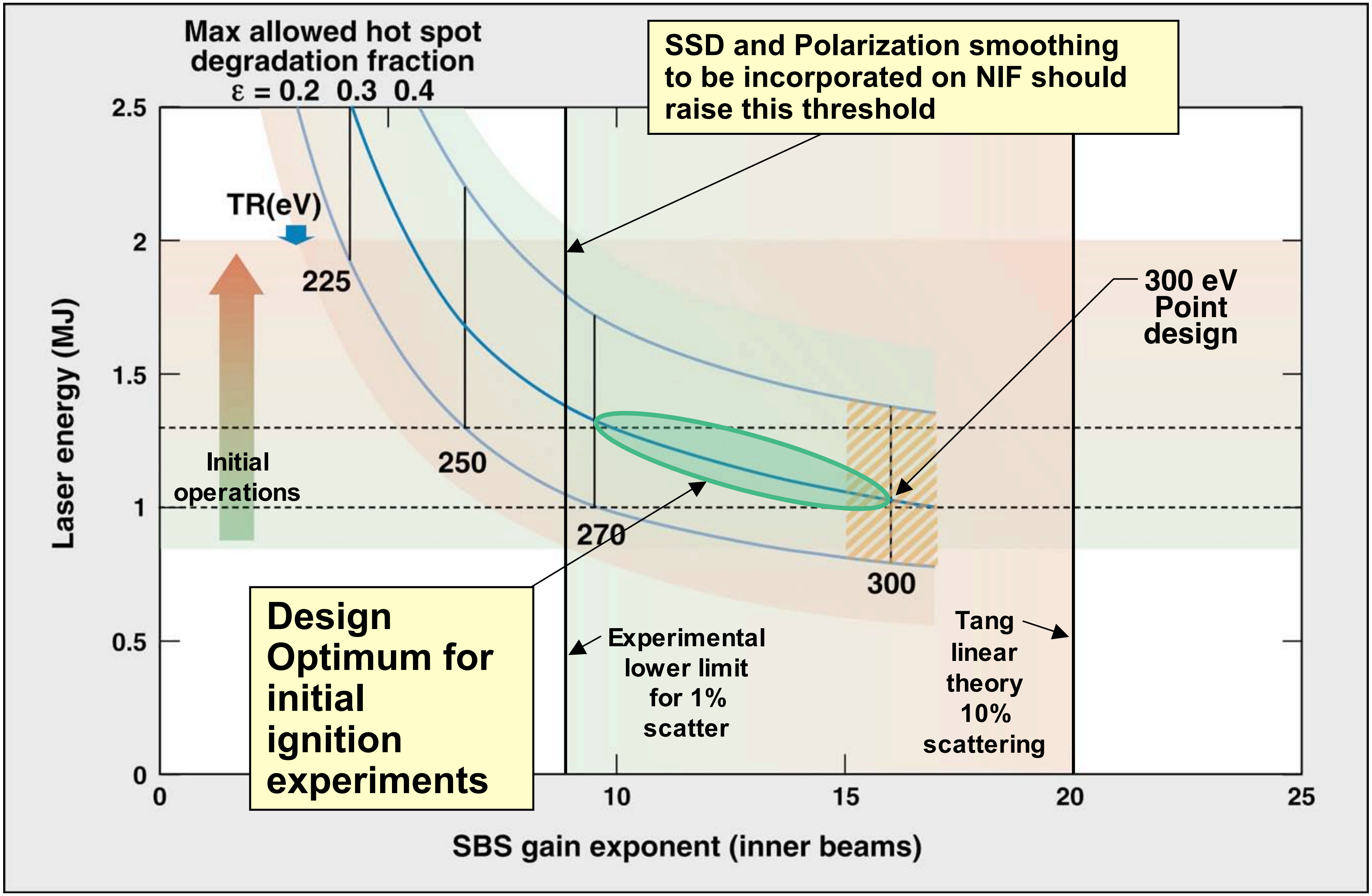
Ignition point design optimization must balance LPI effects, laser performance impacts, and capsule robustness

NIC
The National Ignition Campaign



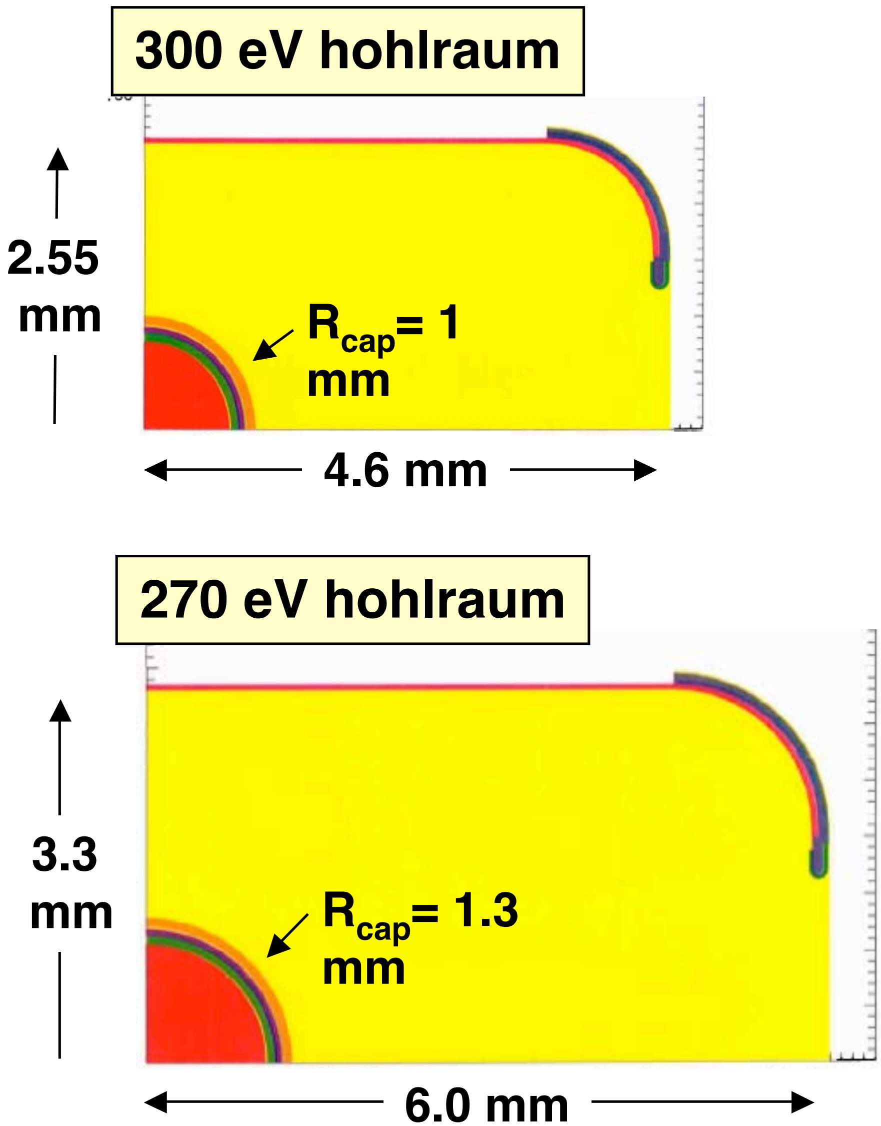
Ignition point design optimization must balance LPI effects, laser performance impacts, and capsule robustness

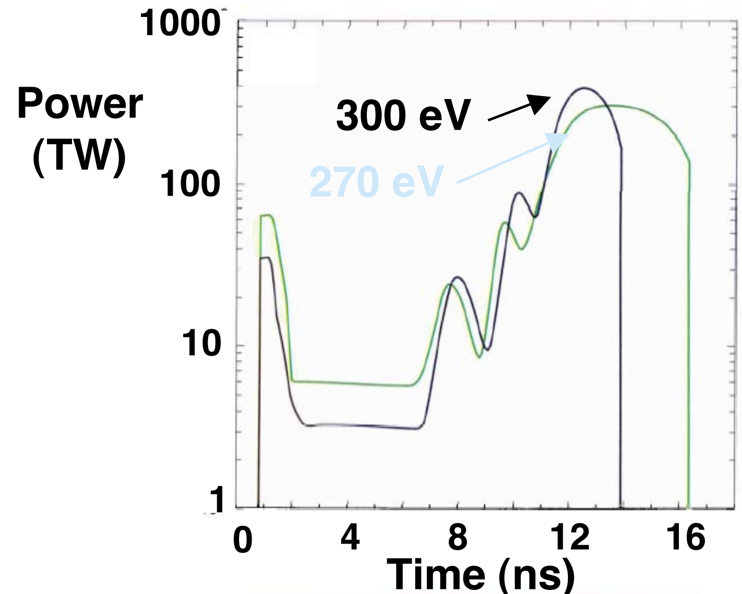
NIC
The National Ignition Campaign

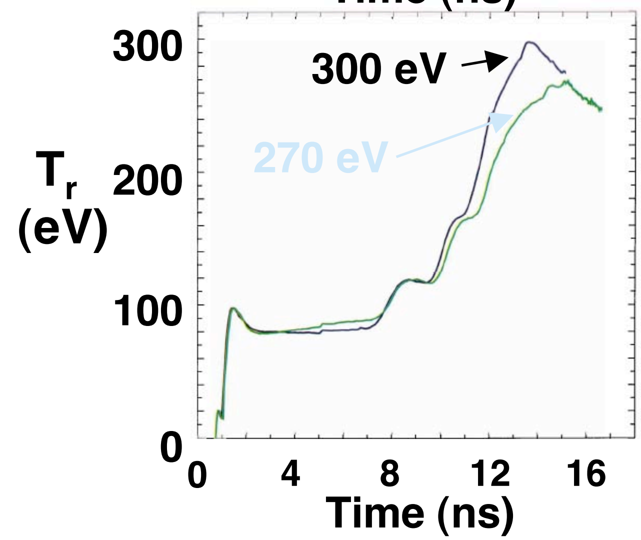


Ignition designs at 300 eV and 270 eV bound the LPI impacts

The National Ignition Campaign







Ignition experiments are organized around Integrated Experiment Teams (IET) and the key diagnostics required for those experiments

The National Ignition Campaign

Laser Performance
- pulse shape
- Power balance
- pointing

– SXI - soft x-ray imager for pointing
– SXD - soft x-ray streak for beam timing

Hohlraum Performance
- X-ray drive
- Symmetry

– FABS and NBI - backscattered light
– Dante - thermal x rays
– FFLEX - hard x-rays from high energy electrons
– GSXI - gated low energy x rays for LEH closure
– GXD - gated multi-keV xrays for symmetry

Capsule Performance
- shock timing
- Ablation rates
- Equation of state
- Hydro instability

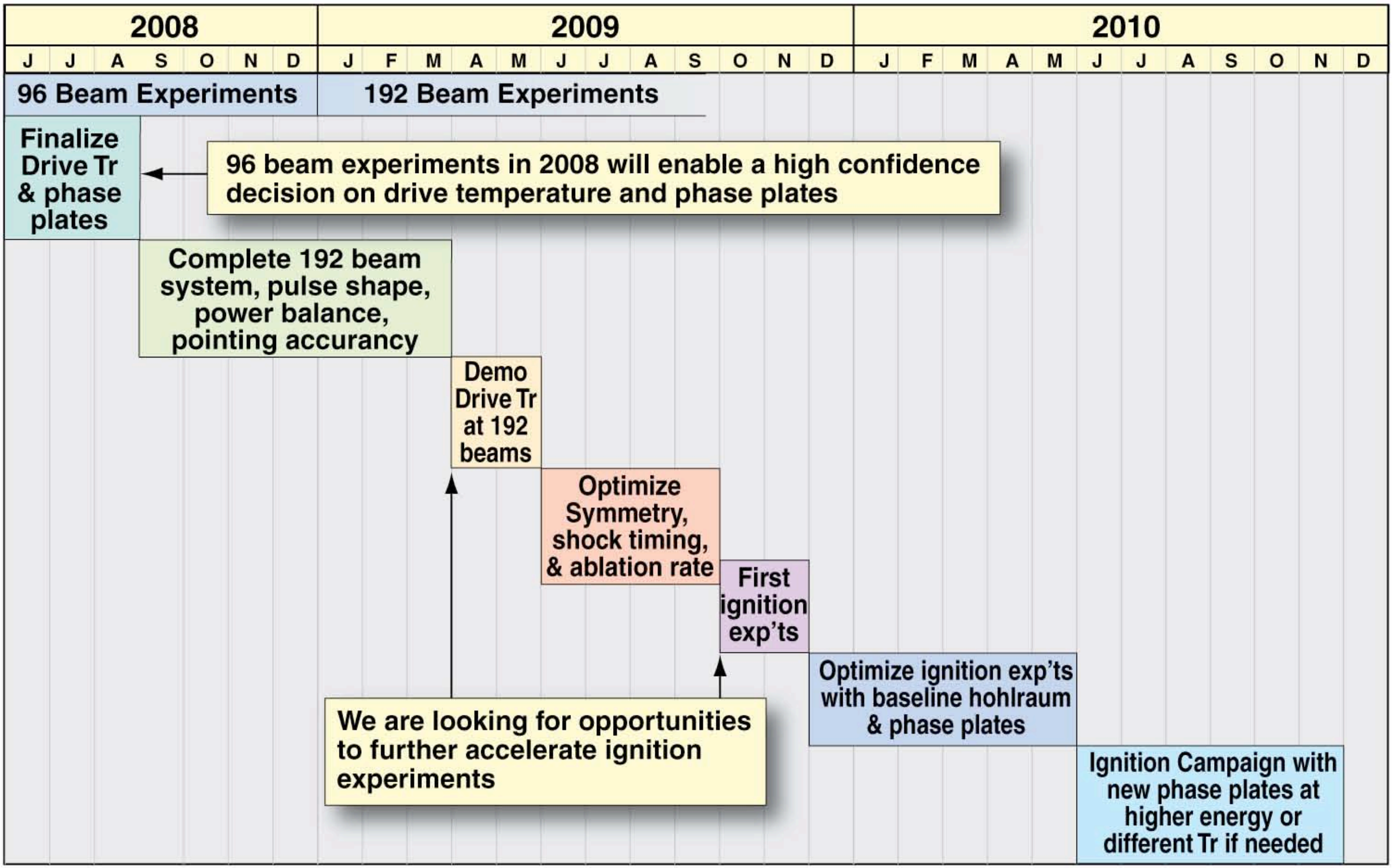
– VISAR - optical interferometer for shock timing
– SOP - streaked optical emission for shock timing
– Cu collection - ablation dynamics
– Proton spectrometer - ablation dynamics

Ignition
- point design
- implosion diagnostic signatures

– ARC - compton scattering for dense fuel imaging
– Neutron imaging
– Gamma bang time
– NTOF - neutron spectroscopy
– MRS - high resolution neutron spectroscopy
– Protex - knock-on protons for yield
– Cu activation for yield
– Carbon activation - tertiary neutrons
– HEXRI - x-ray core

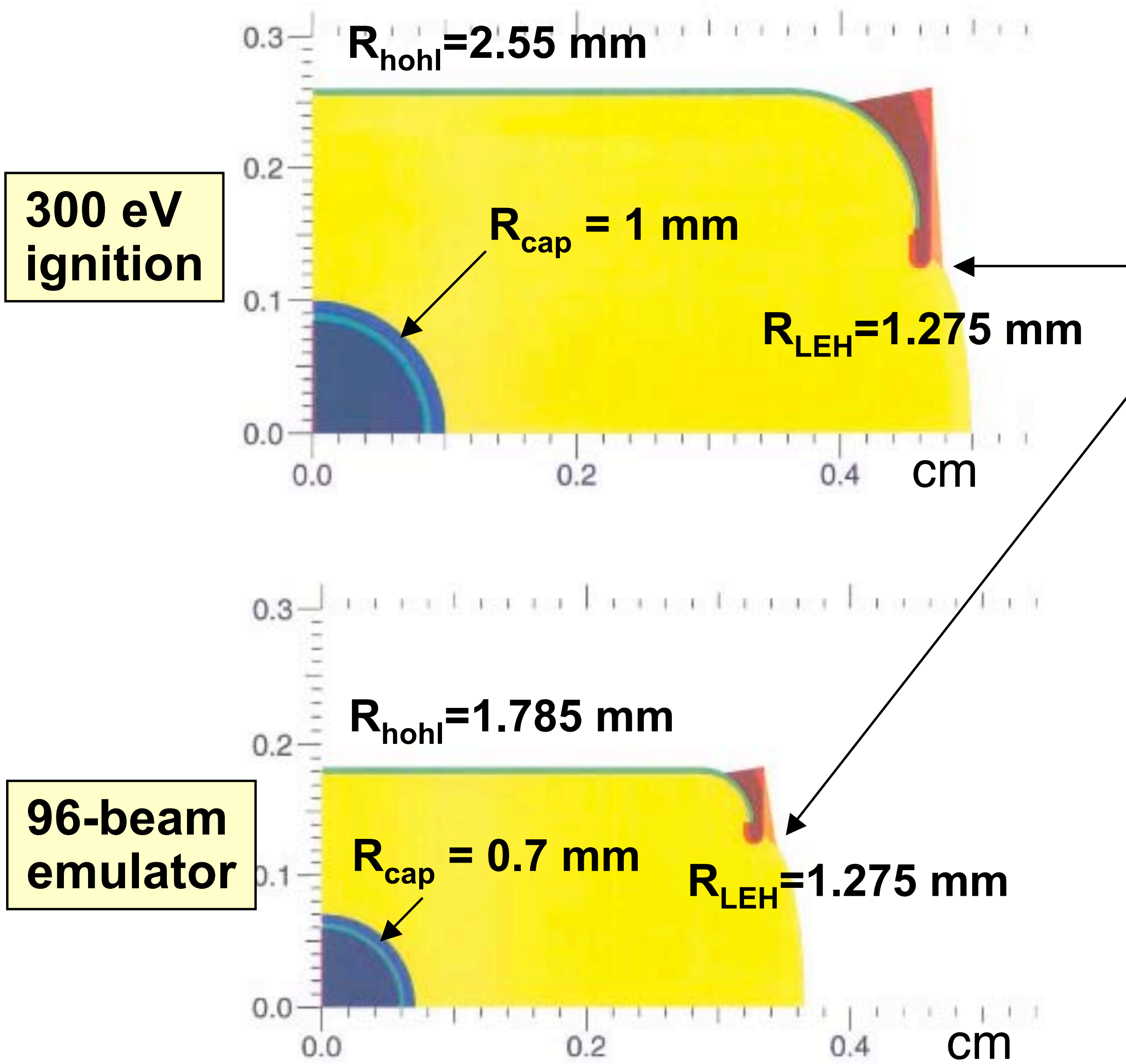
We are developing an ignition program plan which would enable the first ignition experiments in 2009

The National Ignition Campaign



We emulate ignition hohlraum plasma conditions at 96-beams by scaling the hohlraum to 70% of ignition size

The National Ignition Campaign

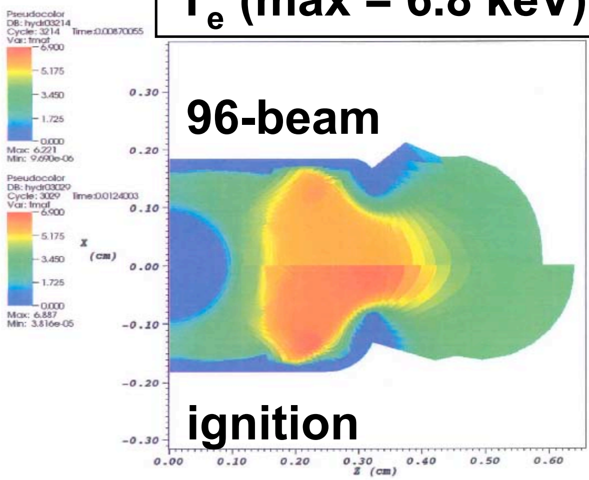


- **We use full size phase plates so the LEH is not scaled**
- **A 270 eV emulator will use a 1.3 scale hohlraum and 1.3 scale inner phase plates but same outer beam phase plates**

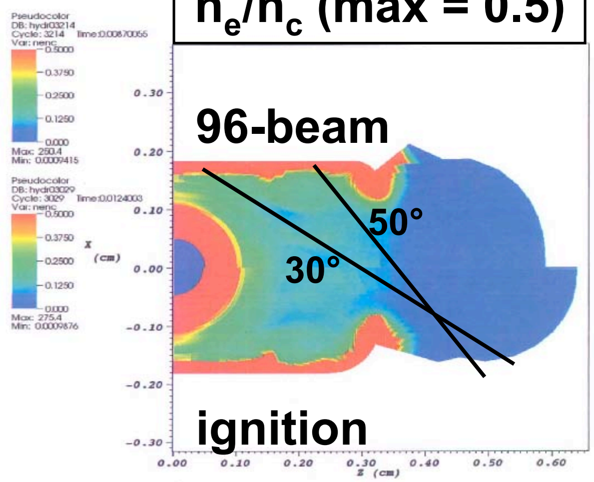
LPI gains, as well as densities and temperatures, are close to those in the ignition design

The National Ignition Campaign

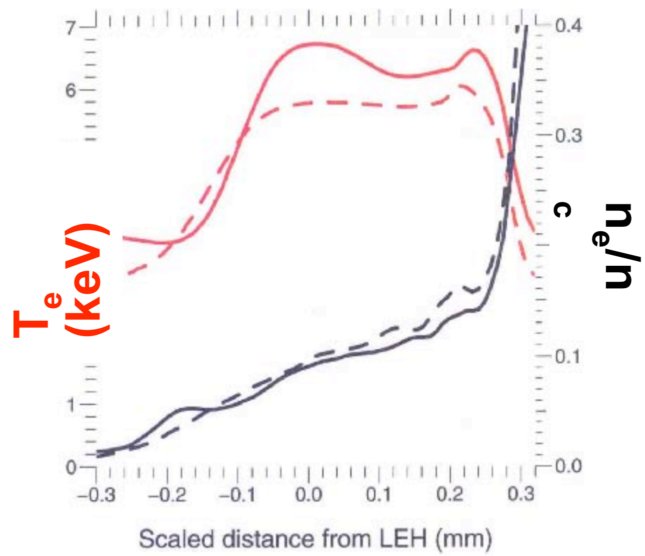
T_e (max = 6.8 keV)



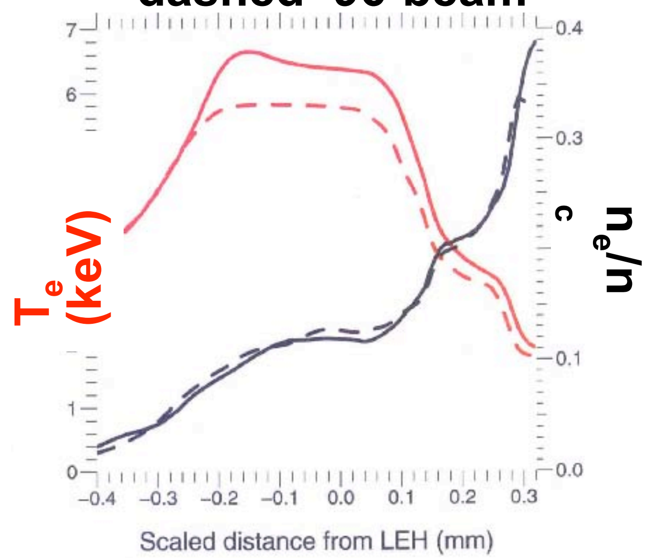
n_e/n_c (max = 0.5)



50° cone; dashed=96-beam



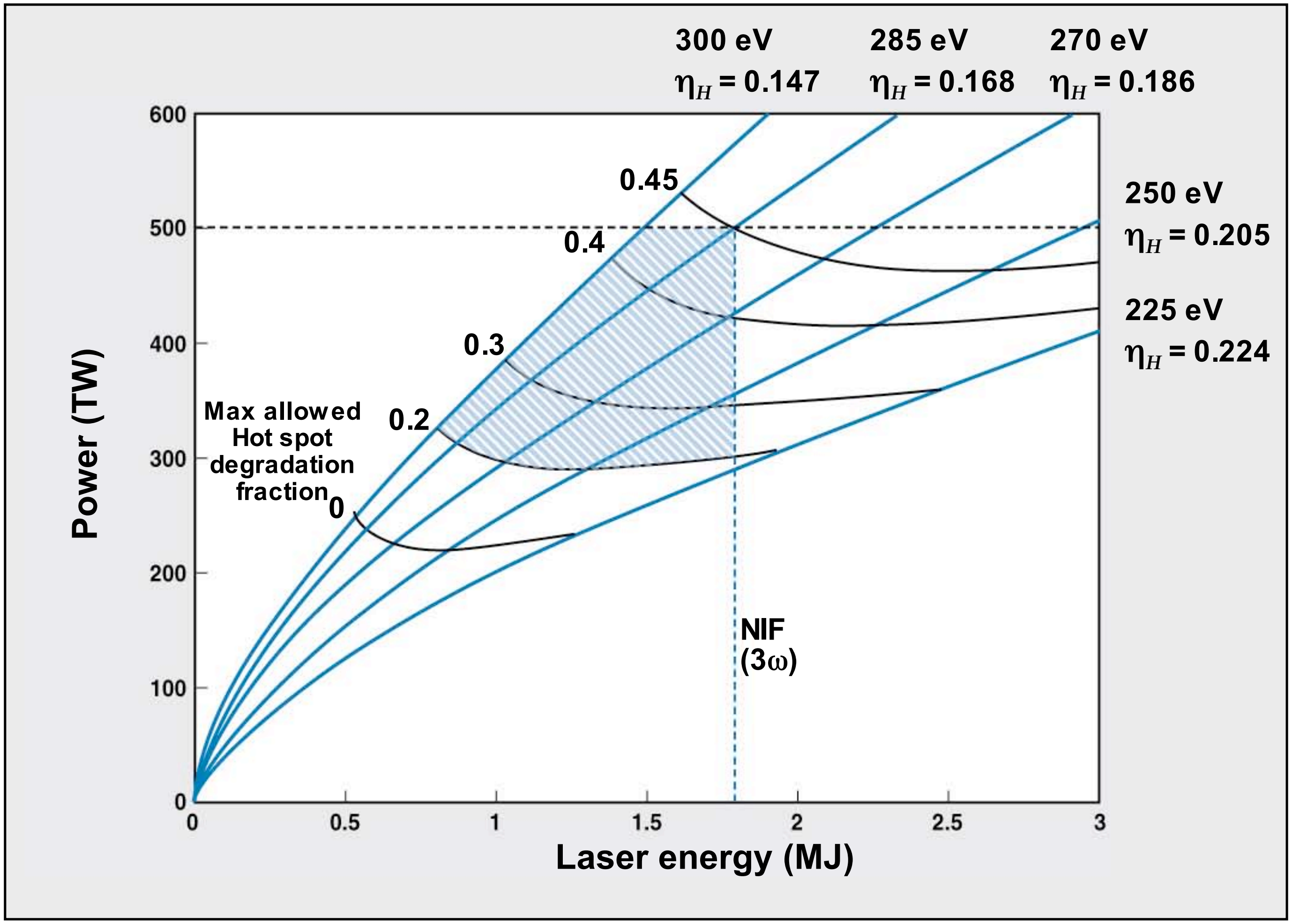
Properties along 30° cone dashed=96-beam



- At the same laser intensity, the LPI gain for the 96 beam targets is ~70% of that for the igintion target
- The gain will be varied by adjusting the intensity of the interaction beam to determine the LPI operating limits

We will use the 96 beam experiments to pick the operating point for the first ignition experiments

NIC
The National Ignition Campaign



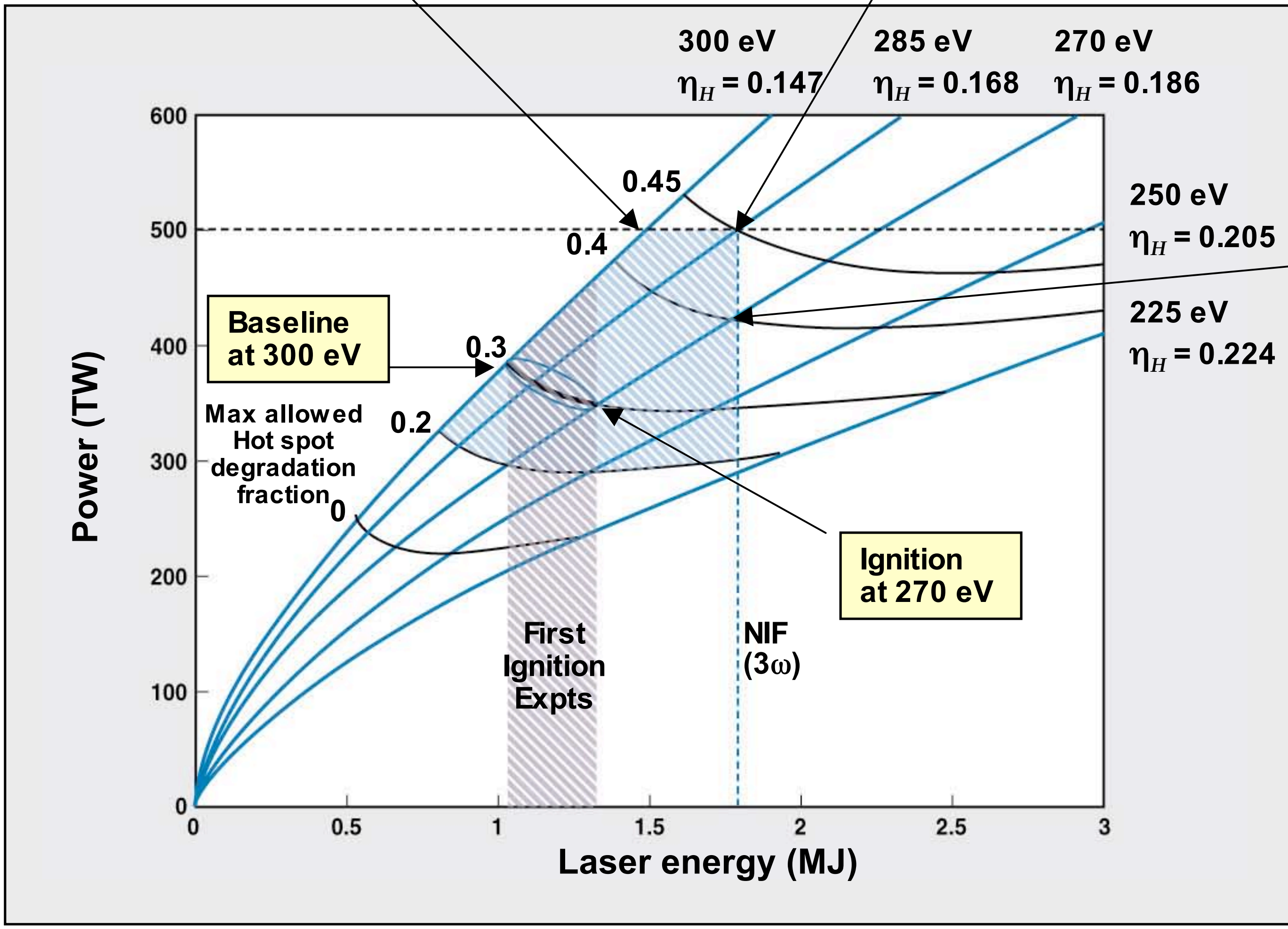
We will use the 96 beam experiments to pick the operating point for the first ignition experiments

The National Ignition Campaign

A 300 eV design uses all of NIF's available power before reaching the energy limit - the minimum energy design

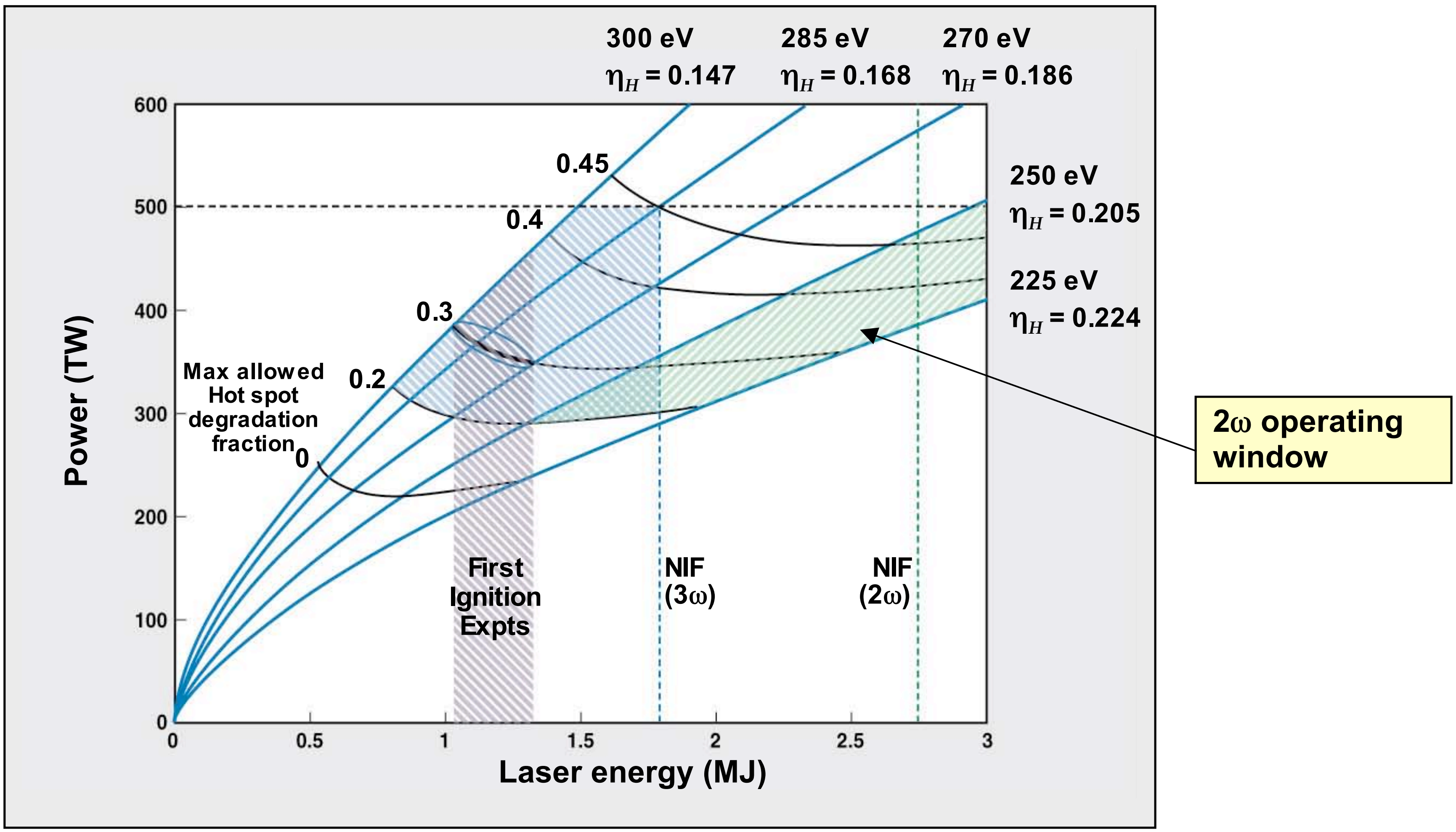
Maximum Capsule robustness is achieved with a hohlraum that can utilize both the full power and energy of NIF

A 270 eV design uses all of NIF's energy before reaching the power limit - the minimum LPI design



Operating at 2ω provides an opportunity for high yields

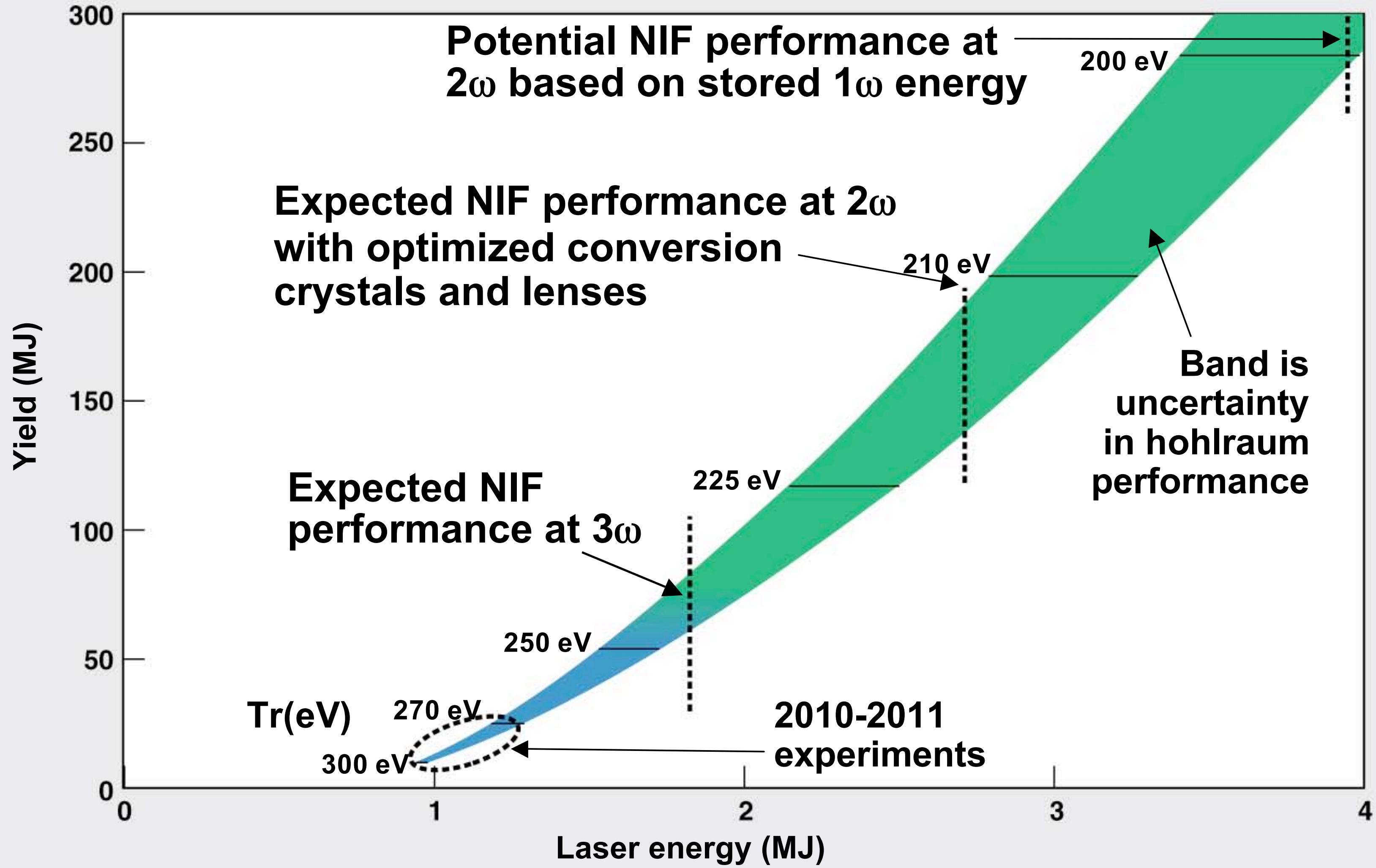
The National Ignition Campaign



Ultimately, yields well in excess of 100 MJ may be possible on NIF

NIC
The National Ignition Campaign

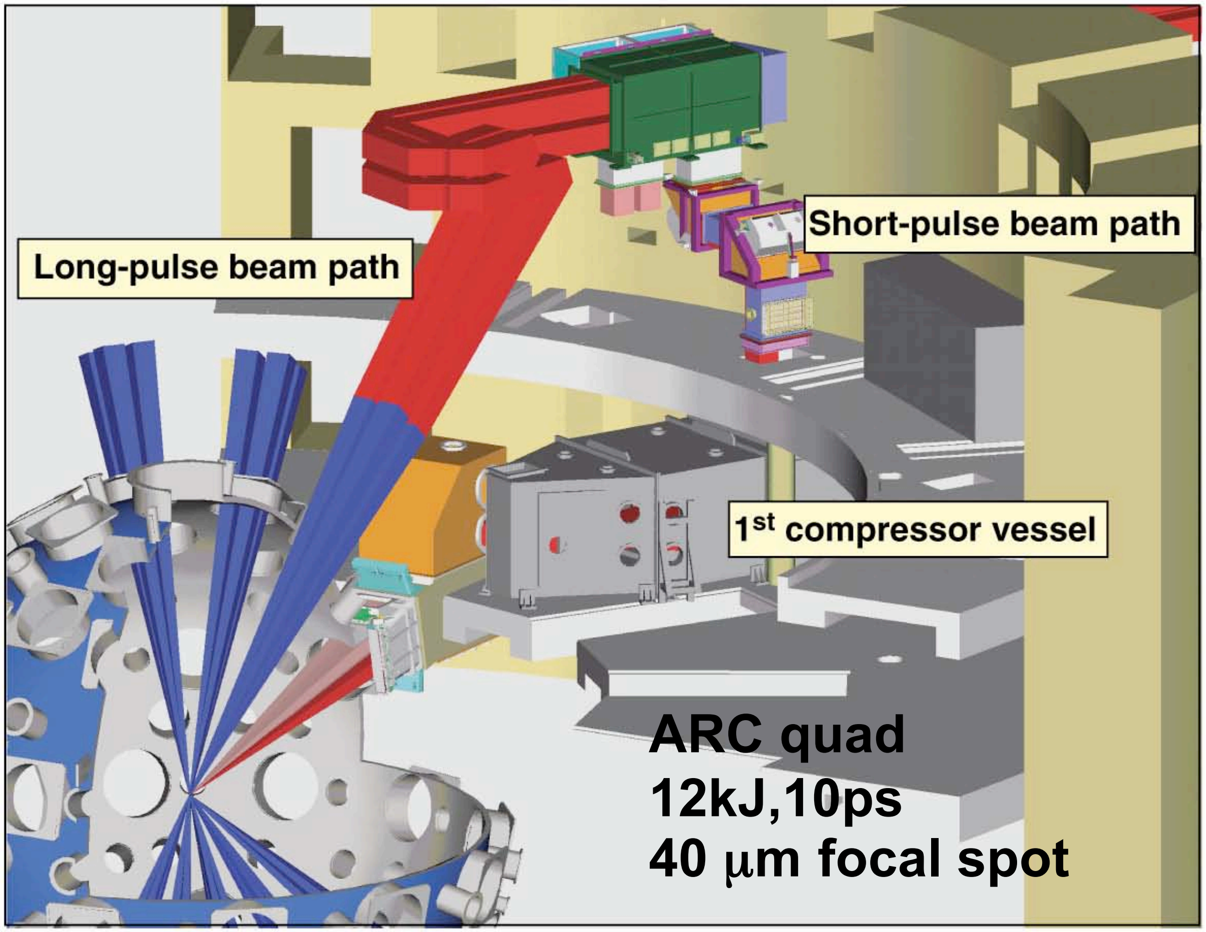
Yields versus laser energy for NIF geometry hohlraums



NIF-0107-13186

ARC (Advanced Radiographic Capability) is being implemented on NIF as a major diagnostic for NIC

NIC
The National Ignition Campaign



- A "Quad" of NIF beams is compressed to deliver a 1-10 ps pulse
- Uses include backlighter for dense cold fuel in ignition targets and a variety of high optical depth HEDP targets
- NIF can provide a full scale high gain compressed fuel assembly for fast ignition
- Up to 5 short pulse quads could be deployed on NIF for fast ignition

After 15 years, all of the pieces for ignition are almost in place

The National Ignition Campaign

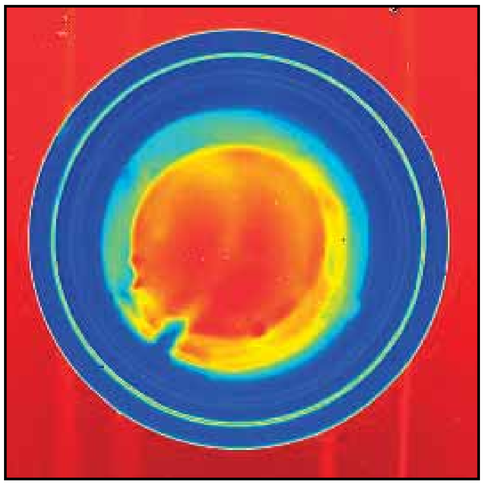
- The NIF laser and the equipment needed for ignition experiments, including high quality targets, will be available in 22 months
- We have an ignition point design target near 1 MJ with a credible chance for ignition during early NIF operations
- The Laser Plasma Interaction (LPI) uncertainty in the ignition point design is bounded by about 300 kJ in laser energy or by a range of hohlraum temperatures of 270-300 eV
- We have an Early Opportunity Shots (EOS) campaign with 96 beams planned to start in 14 months which will allow us to choose the optimum hohlraum temperature and laser energy for initial ignition experiments.
- The initial ignition experiments only scratch the surface of NIF's potential which includes high yields with green light and greatly expanded opportunities for the uses of ignition by decoupling compression and ignition in Fast Ignition (FI).

NIC

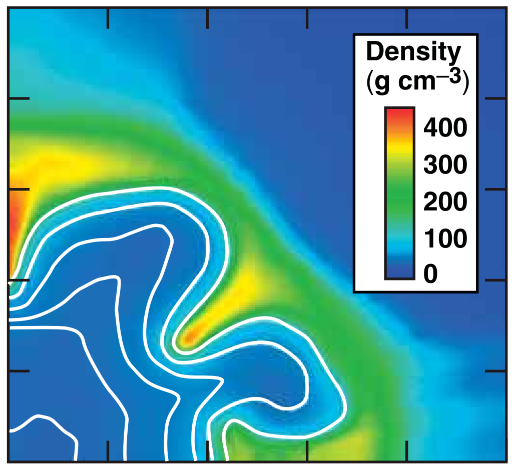
NATIONAL
IGNITION
CAMPAIGN

The Laboratory for Laser Energetics (LLE) Validates ICF Ignition Concepts

UR LLE



Cryogenic DT capsule implosions



2-D simulation of PDD NIF implosion with a gain of ~ 17

OMEGA EP under construction

J. M. Soures
University of Rochester
Laboratory for Laser Energetics

IFE Science and Technology Strategic Planning Workshop
San Ramon, CA
24–27 April 2007

Summary

The Laboratory for Laser Energetics validates ICF ignition concepts

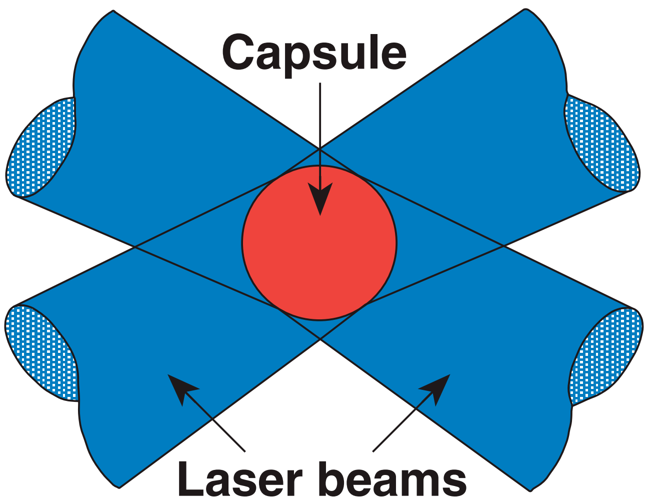
UR LLE

- The baseline direct-drive ignition target for the NIF is a thick cryogenic DT shell enclosed by a thin plastic shell.
- DT ice-layer roughness <1-μm rms are routinely achieved and cryogenic D_2 and DT implosions are ongoing.
- Polar direct drive (PDD) will allow direct-drive ignition experiments while NIF is configured for indirect drive.
- OMEGA provides critical data for indirect-drive ignition (IDI).
- OMEGA EP (high energy petawatt) will be completed in April 2008 and integrated fast-ignition experiments will begin in 2009.

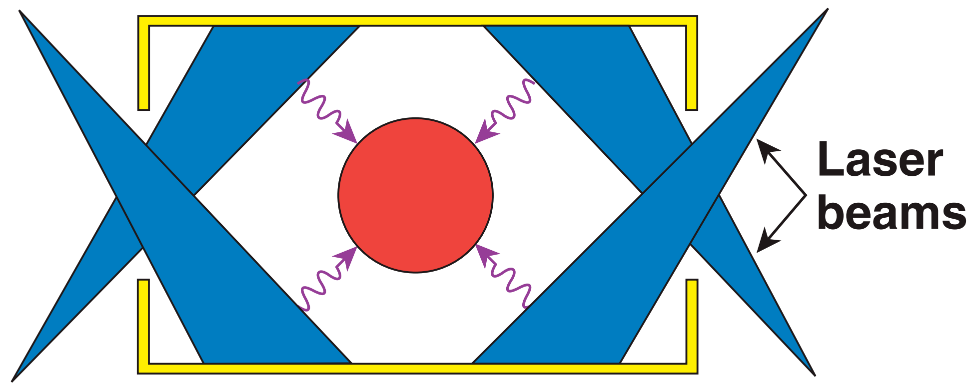
E14220e

The key physics issues of both direct- and indirect-drive ignition are similar

Direct-drive target



Indirect-drive target



Hohlraum using
a cylindrical high-*Z* case

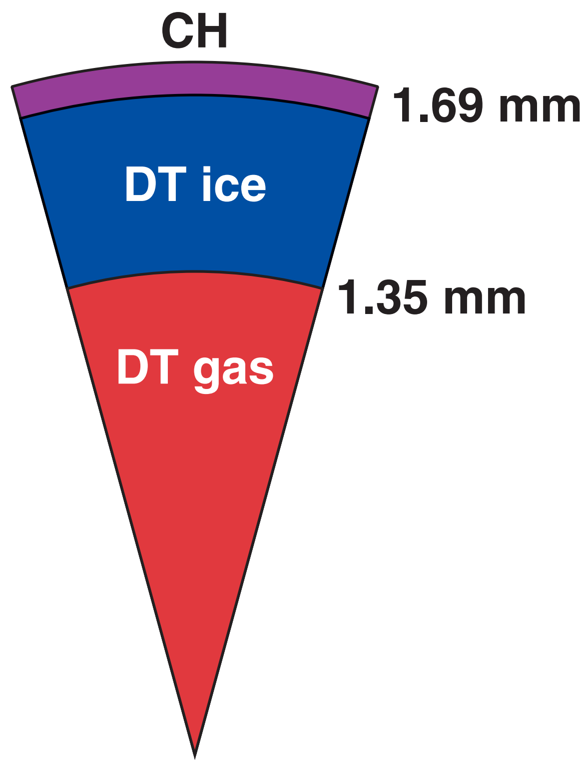
<u>Key issues:</u>

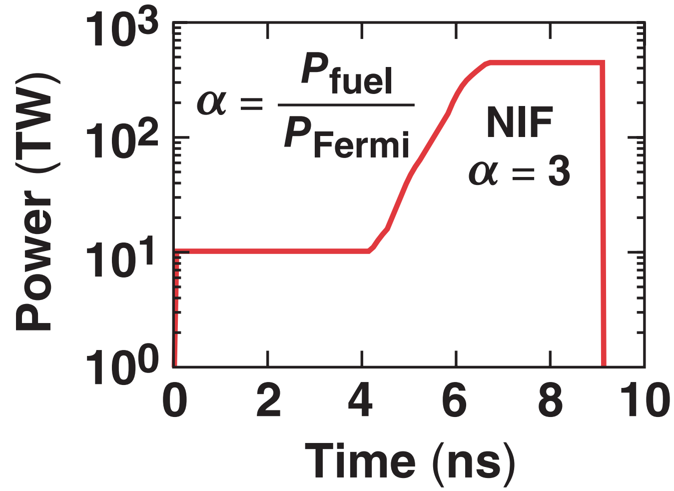
- Energy coupling/drive
- Drive uniformity
- Hydrodynamic instabilities

E6426L

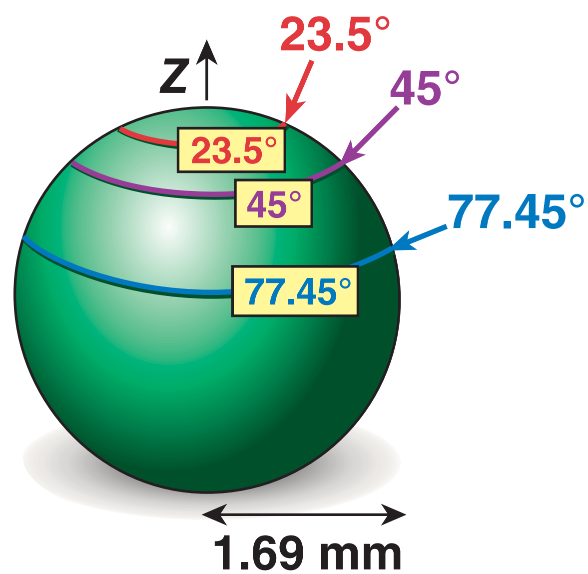
Symmetric Drive

The NIF symmetric direct-drive point design is a thick DT-ice layer enclosed by a thin CH shell





Symmetric Drive



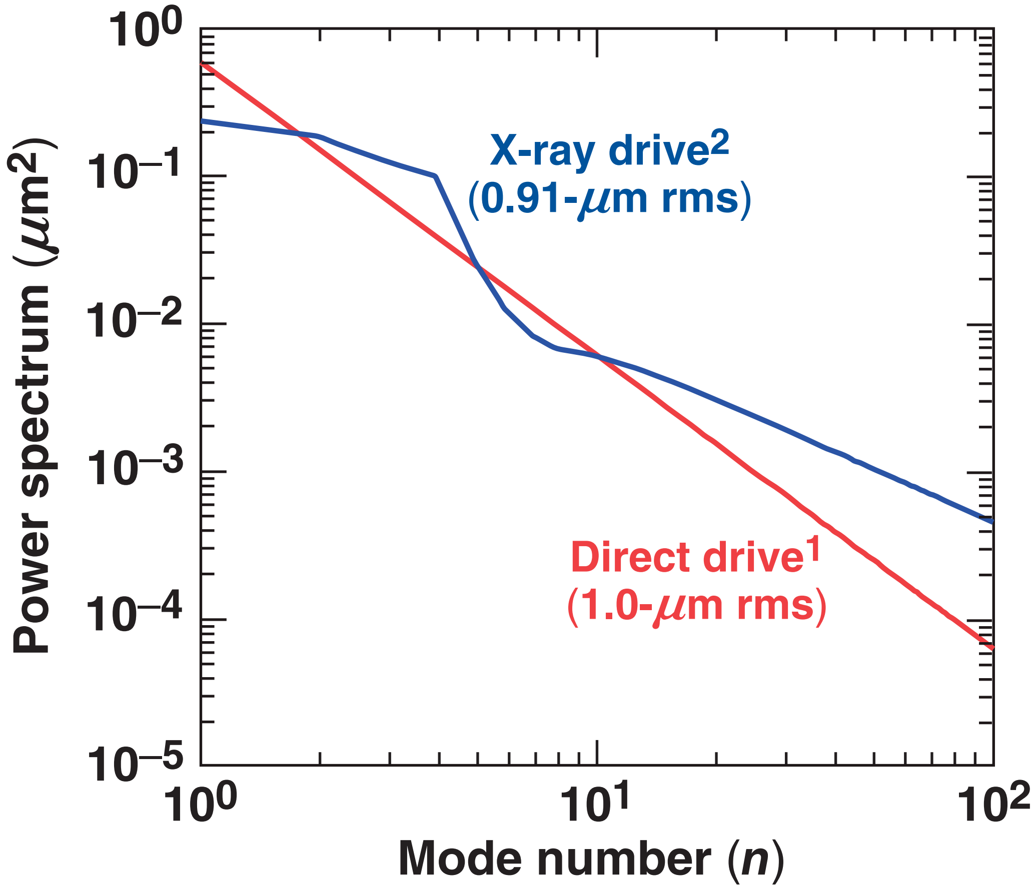
Energy: 1.5 MJ

Absorption fraction: 63%

Gain $\left(\frac{\text{fusion energy out}}{\text{laser energy in}}\right)$: 45

TC5576e

The inner-ice-smoothness requirements are similar for direct- and x-ray-drive ignition



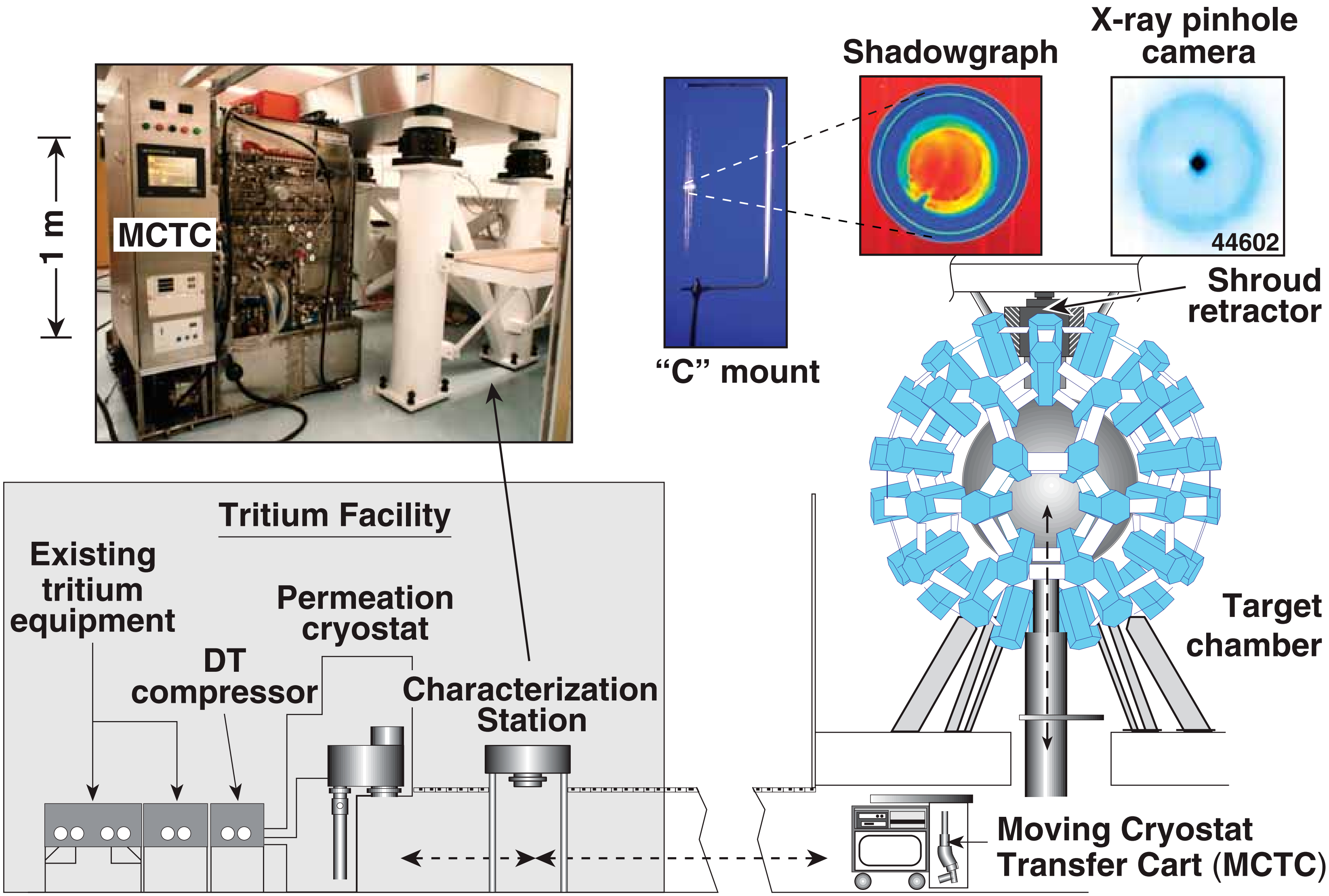
- These requirements are based on detailed multi-dimensional simulations of the implosion performance[1,2]

[1]P. W. McKenty *et al.*, Phys. Plasmas 8, 2315 (2001).
[2]J. D. Lindl *et al.*, Phys. Plasmas 11, 339 (2004).

E15190a

Cryogenic Capsule Development

LLE typically implodes 2 to 4 cryogenic capsules per day, two days per month (DT and D_2)

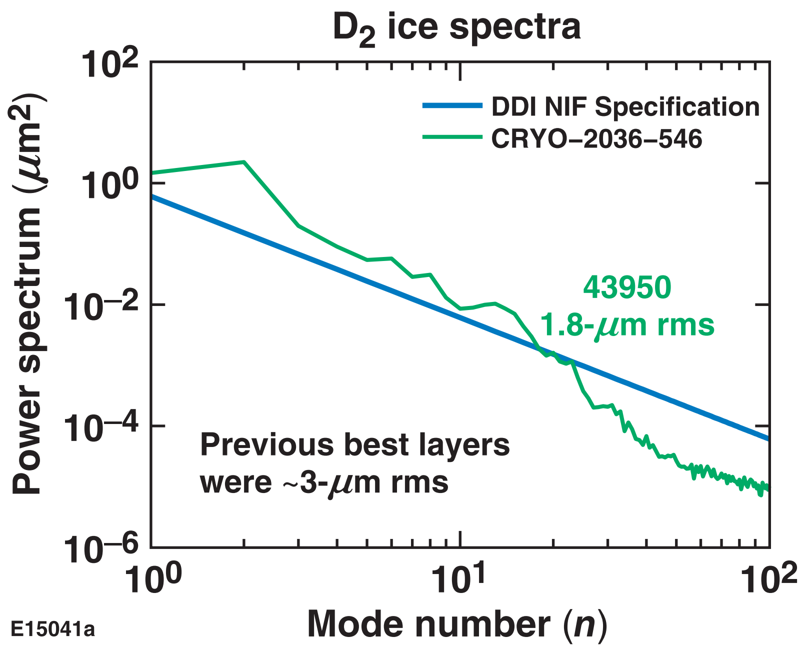


E12062j

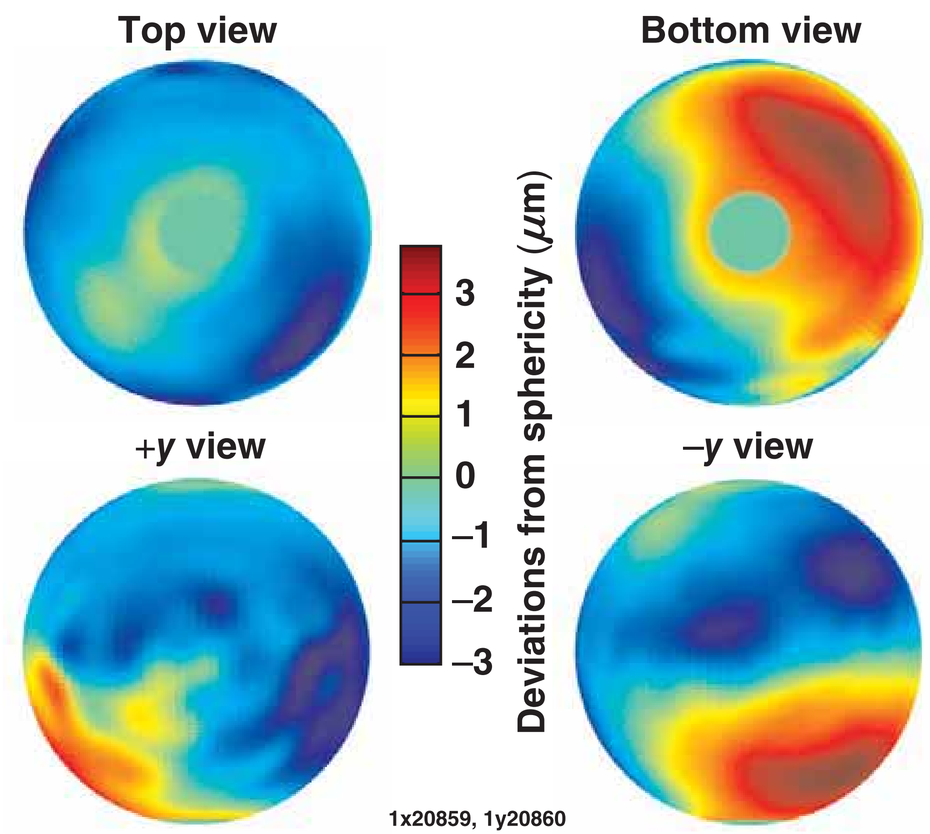
3-D thermal modeling led to a significant improvement in ice smoothness for D_2 capsules (IR layering)

UR LLE

- Layering-sphere upgrades based on thermal modeling
  - Increased the exchange-gas pressure
  - Added a diffuser to the IR laser-fiber input
  - Modified the mount structures to minimize IR absorption (e.g., Au coating)



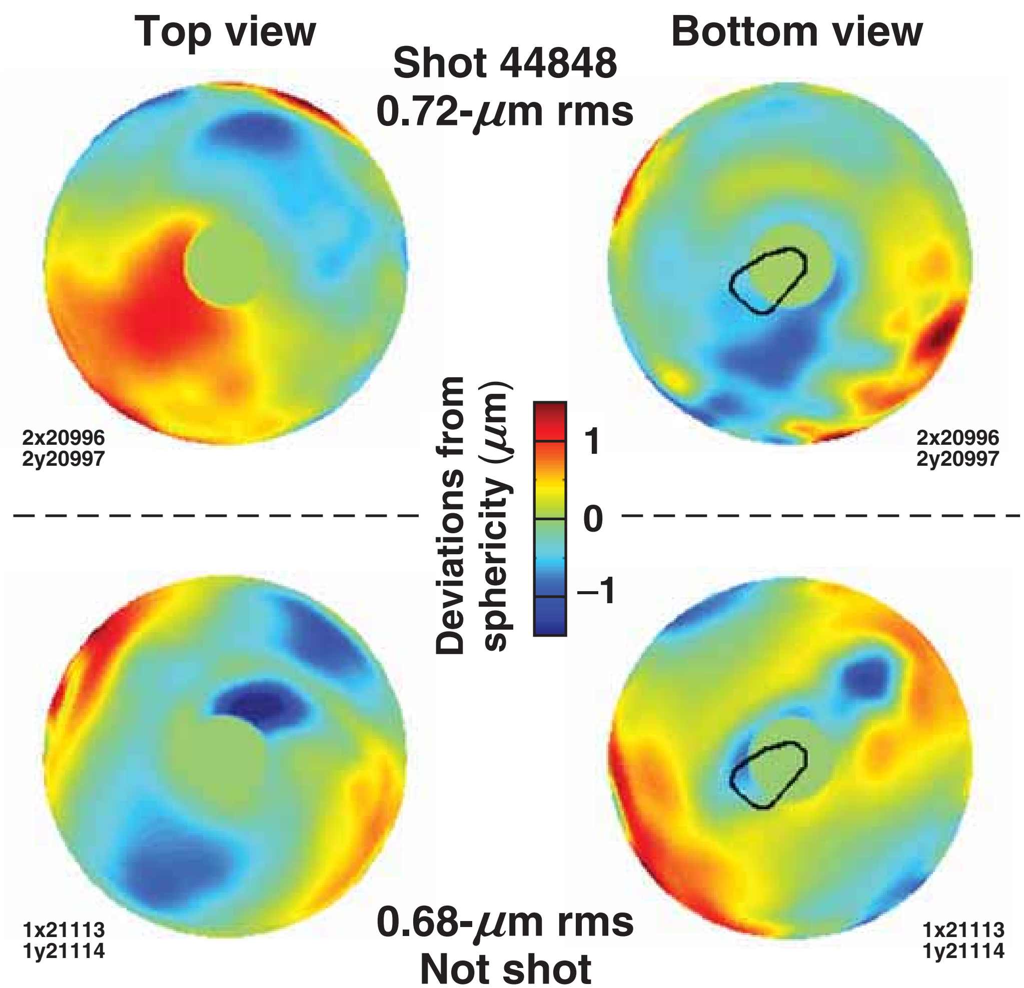
Shot 43950: 1.8-μm-rms D_2 capsule



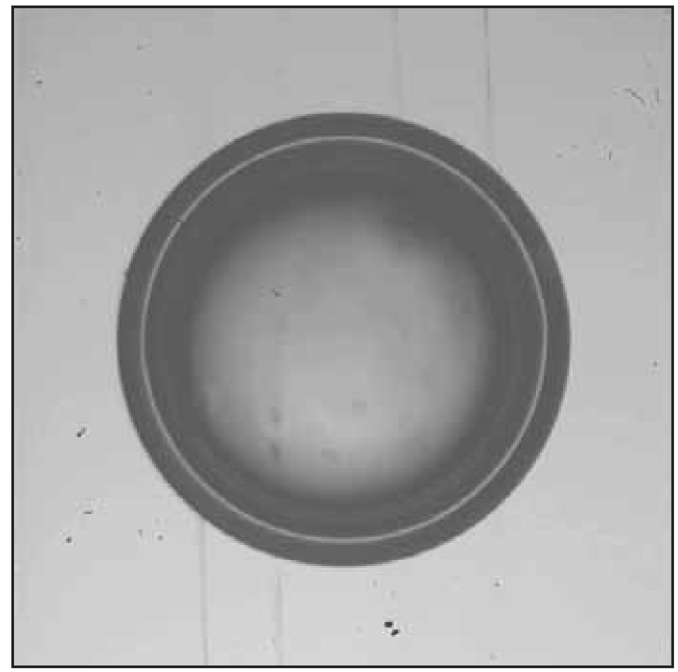
E15041a

1x20859, 1y20860

DT (45:55) targets with an ice roughness of $\lesssim$1-μm rms for all modes are being imploded on OMEGA

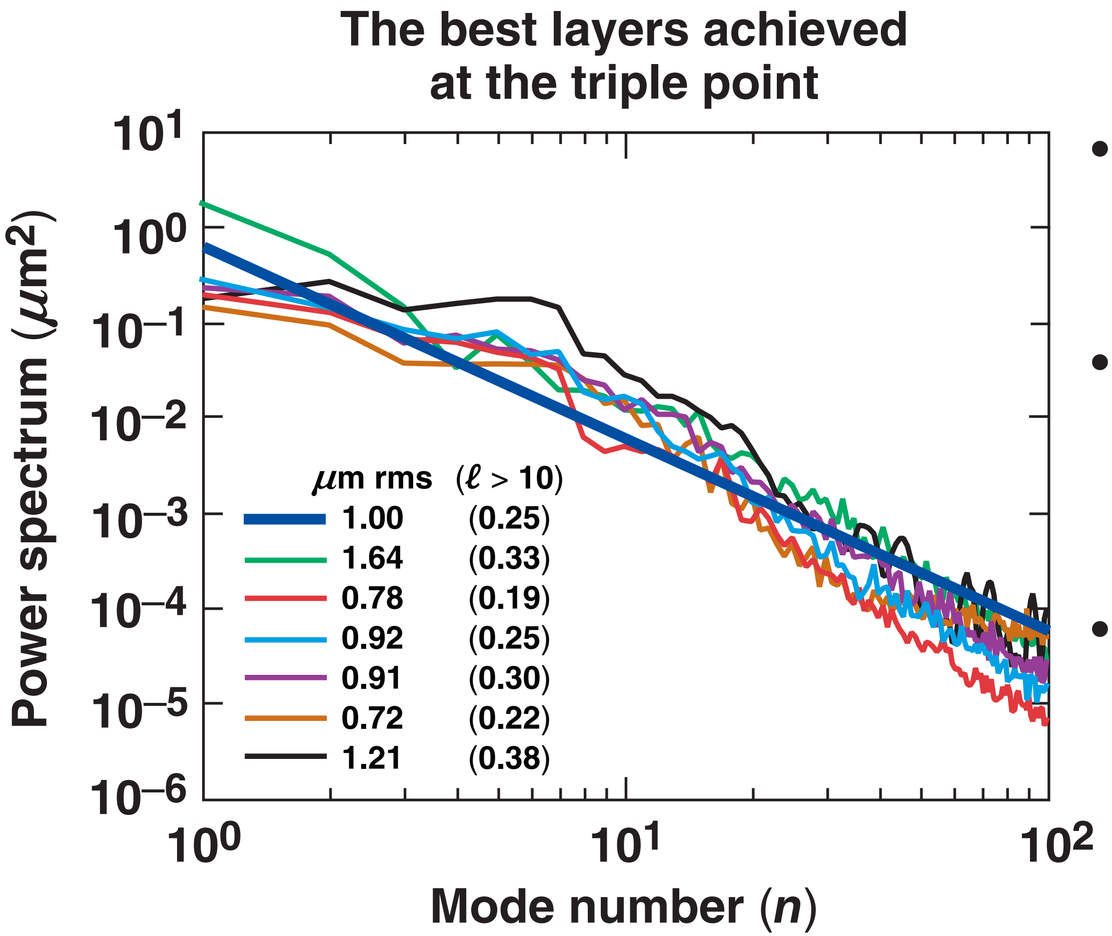


Target for shot 44848



T2270f

More than half of the DT capsules created to date have produced layers with sub-1-μm-rms roughness



- High-mode ($n > 20$) roughness is minimal for "single crystal" layers
- Low-mode roughness ($n < 6$) is due to asymmetries in the triple point isotherm
- Mid-mode roughness ($6 < n < 20$) is likely related to outer-surface features (glue for silks)

E15043b

Direct-Drive Experiments

Hot-spot physics is being carried out on OMEGA with ignition-quality ice

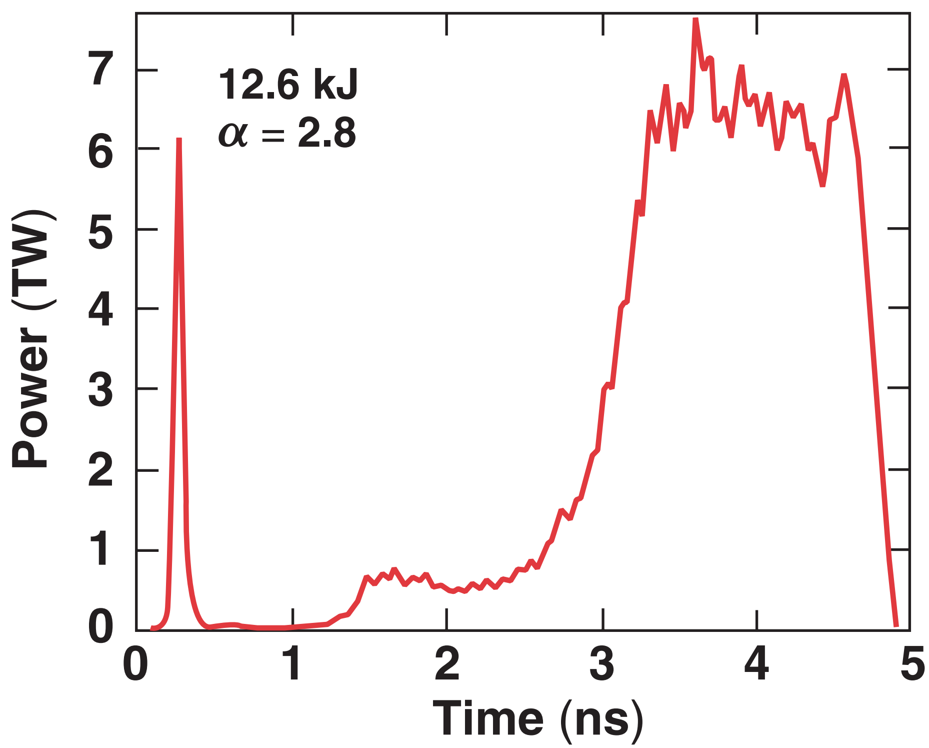
- Fuel assembly (areal density)/convergence
- Core temperature
- Yields
- Laser-energy coupling and preheat
- Performance sensitivity to single beam smoothing
- Performance sensitivity to adiabat shaping
- Performance sensitivity to shell stability (adiabat)

__ DT implosions and __ D_2 implosions have been performed on OMEGA

E15056b

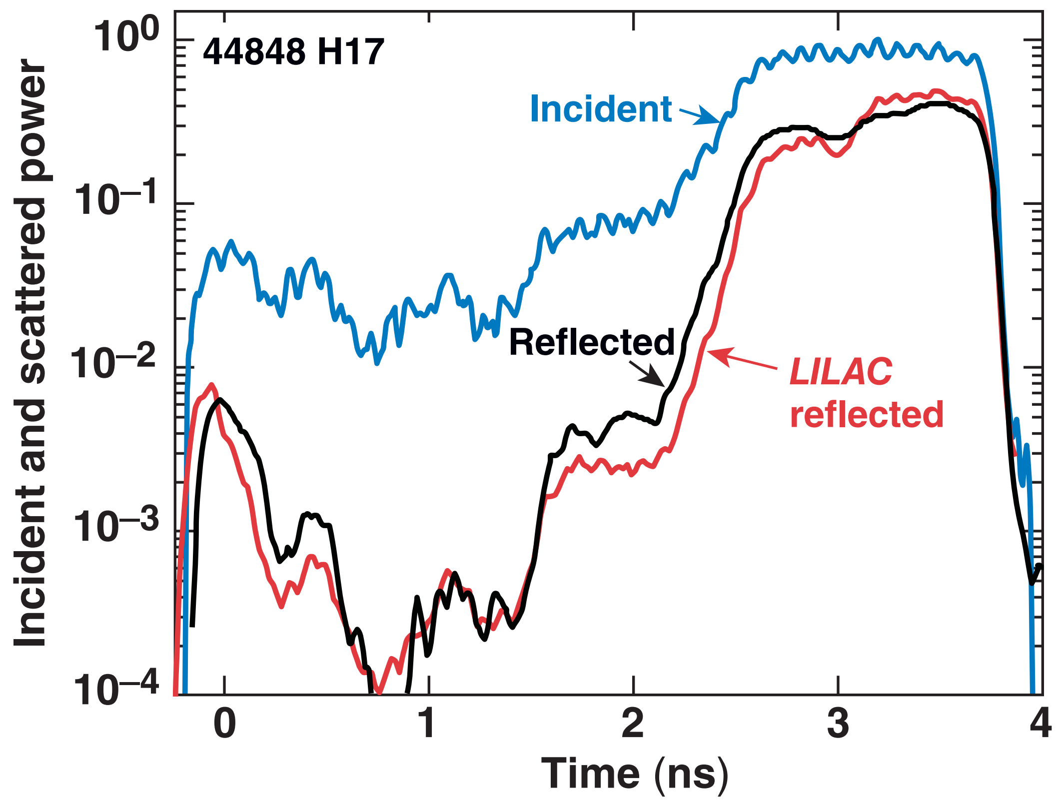
High-contrast pulse shapes are used to place the target on a low adiabat for high compression

- Cryogenic ice-layer smoothness is routinely below 2-μm rms.
- The picket shapes the target adiabat.
- The peak intensity limits the core temperature for continuum measurements.



E15269a

Measured time-resolved scattered-light powers differ from hydrodynamic predictions in subtle ways



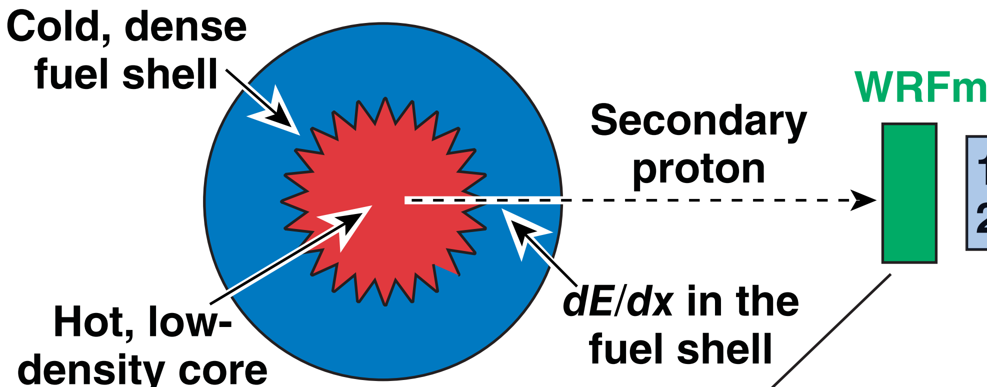
Measured time-integrated absorption = 67% = *LILAC*-predicted absorption

E15210

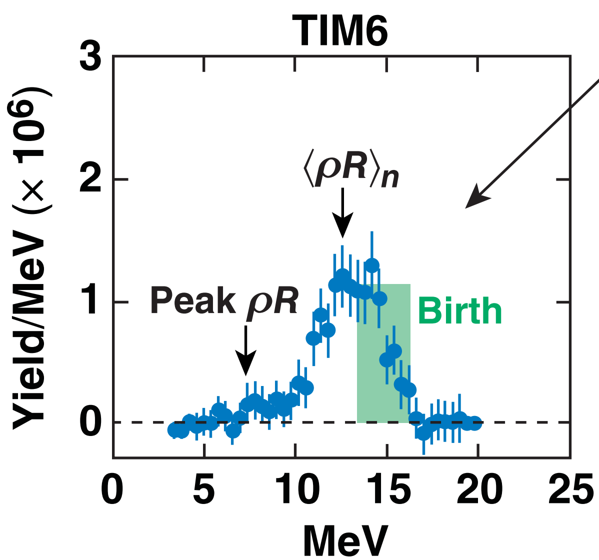
Target: cryogenic DT (95 μm), 5.4-μm CD shell

Direct Drive

The neutron-averaged areal density $<\rho R>_n$ is greater than 100 mg/cm^2 for cryogenic D_2 implosions



1. $D + D \rightarrow {}^3He$ (0.7 MeV) + p
2. ${}^3He + D \rightarrow p$ (12.5–17.4 MeV) + ${}^4He$



- *dE*/*dx* corresponds to $<\rho R>_n \sim$ 100 to 110 mg/cm^2 over several lines-of-sight
- Low-energy tail suggests peak ρR approaches 200 mg/cm^2

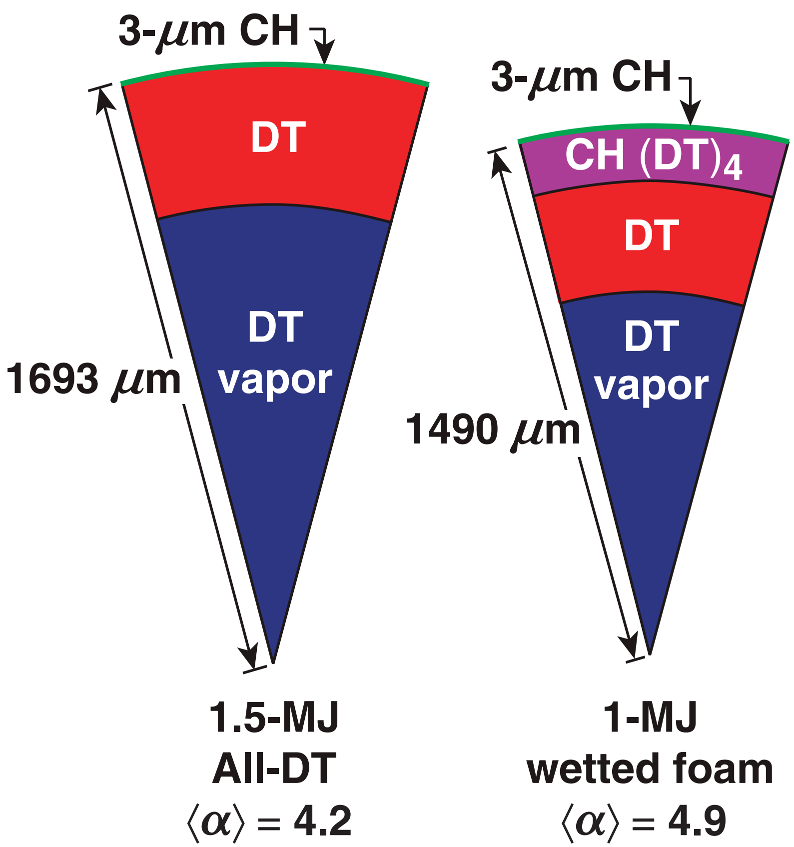
Further analysis is underway to infer a $\rho R(t)$ by convolving the neutron emission rate with the measured proton spectrum*

*V. A. Smalyuk *et al.*, Phys. Rev. Lett. 90, 135002 (2003).

E15270a

Wetted-Foam Design

Wetted foam provides higher laser absorption, allowing a thicker shell and greater stability than the all-DT baseline target at 1 MJ



- The foam density balances higher absorption with increased radiative preheat.
- The foam-layer thickness is chosen so the foam is entirely ablated.

	All-DT	Scaled All-DT	Wetted-foam
Energy (MJ)	1.5	1.0	1.0
Target radius (μm)	1695	1480	1490
Absorption (%)	**65**	**59**	**86**
$A/\Delta R$ (%)	30	33	11
1-D gain	45	40	49

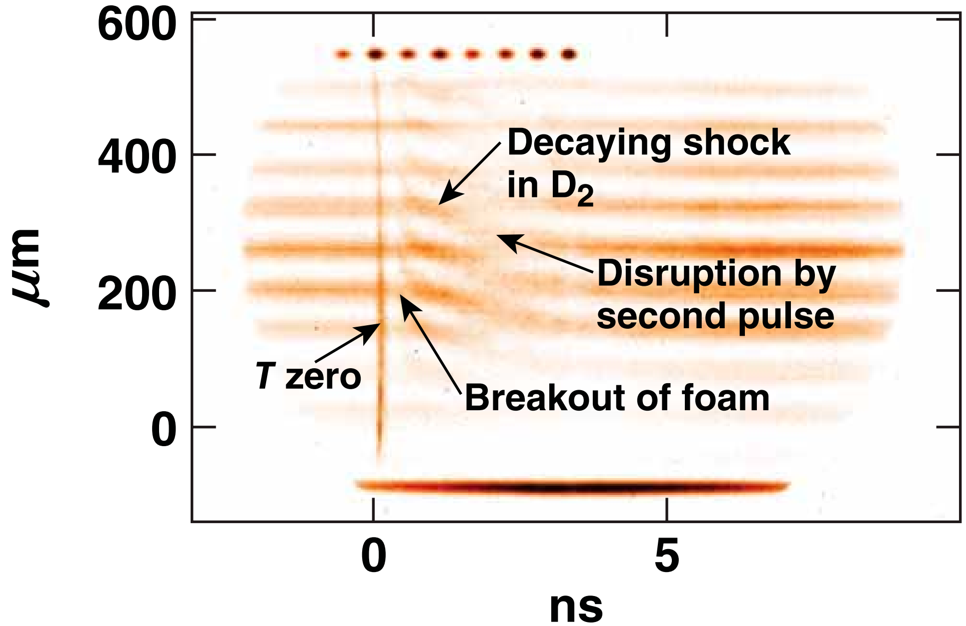
The 1-D, 1-MJ wetted-foam target gain is 49.

TC7449

Both planar and spherical wetted-foam experiments have begun at LLE

- VISAR has been used to diagnose shock speeds in planar experiments with foams wetted with liquid D_2, driven by two 100-ps pulses.

VISAR-2 Shot 34099

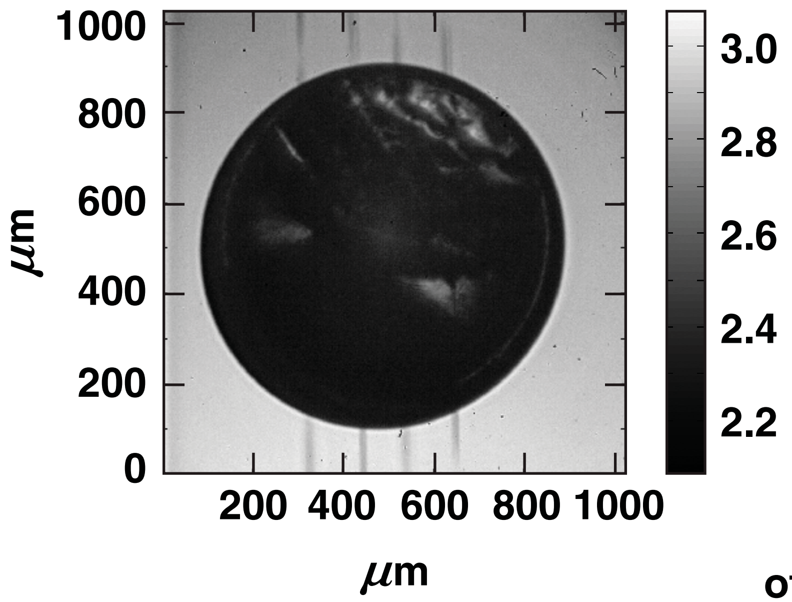


- Planar cryogenic experiments will address shock timing and coupling efficiency.
- Progress with β-layering of cryogenic DT targets at LLE gives confidence in high-quality wetted-foam layering.

Future Experiments

Foam targets are produced by General Atomics and filled and diagnosed at LLE

- Ice roughness in cryogenic wetted-foam targets is currently diagnosed with limited sensitivity using optical shadowgraphy.
- With optical illumination it is difficult to distinguish the various interfaces and layers.
- X-ray phase-contrast imaging is being implemented at LLE, promising greater sensitivity.



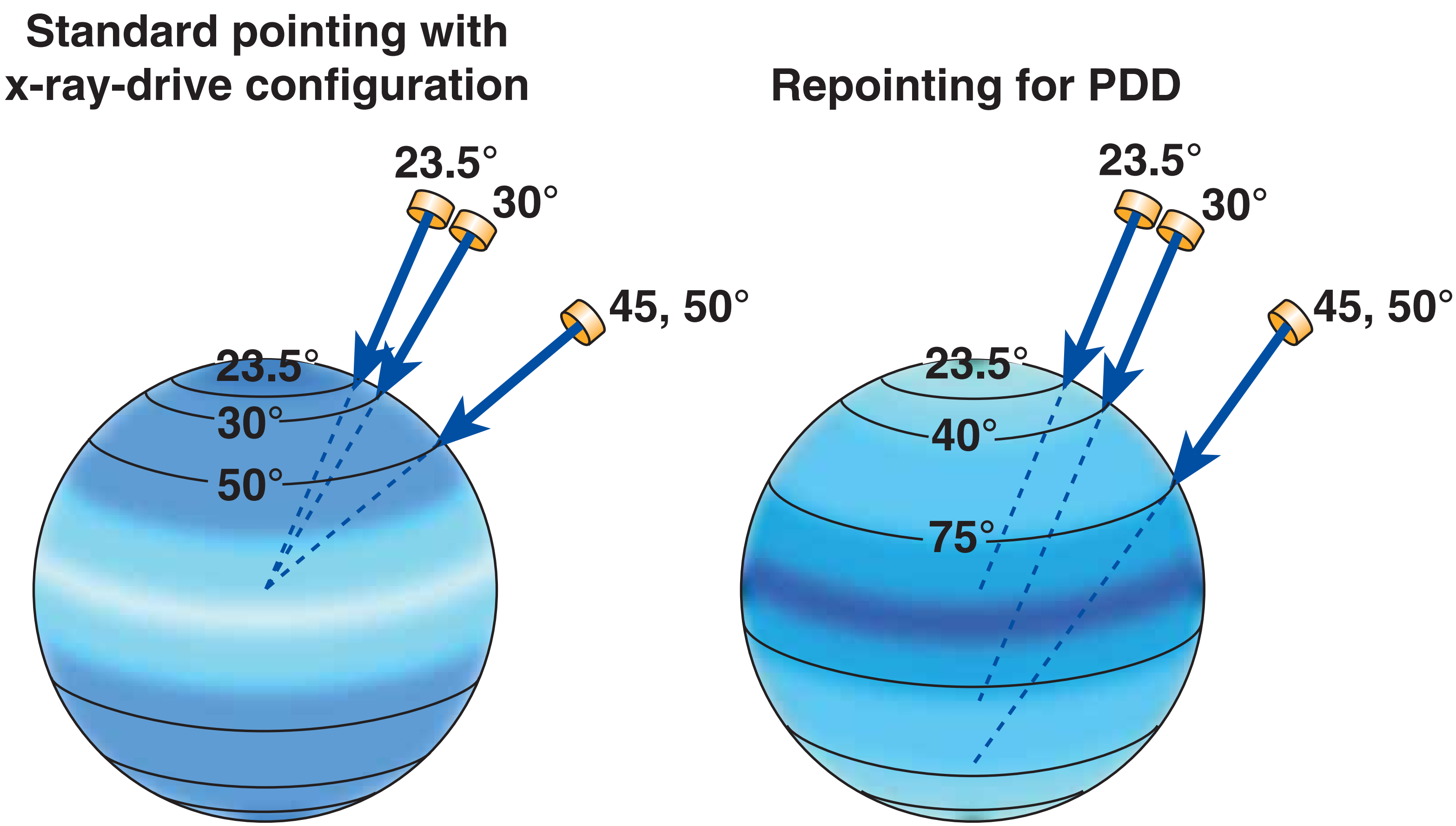
Inner surface visible using optical Illumination

Phase-contrast image of a cryogenic DT-filled foam target*

*Bernard Kozioziemski, private communication (2006).

Polar Direct Drive

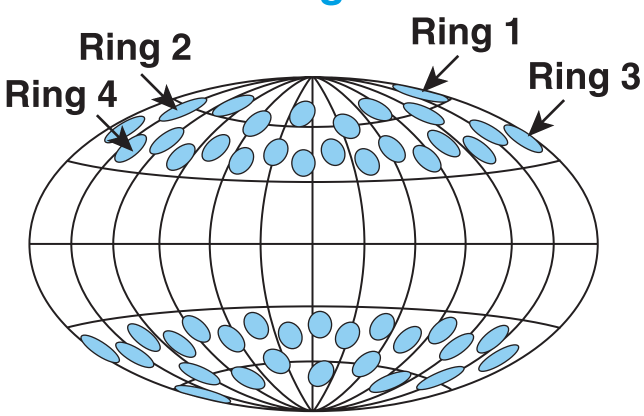
Direct drive can achieve ignition while the NIF is in the x-ray-drive configuration

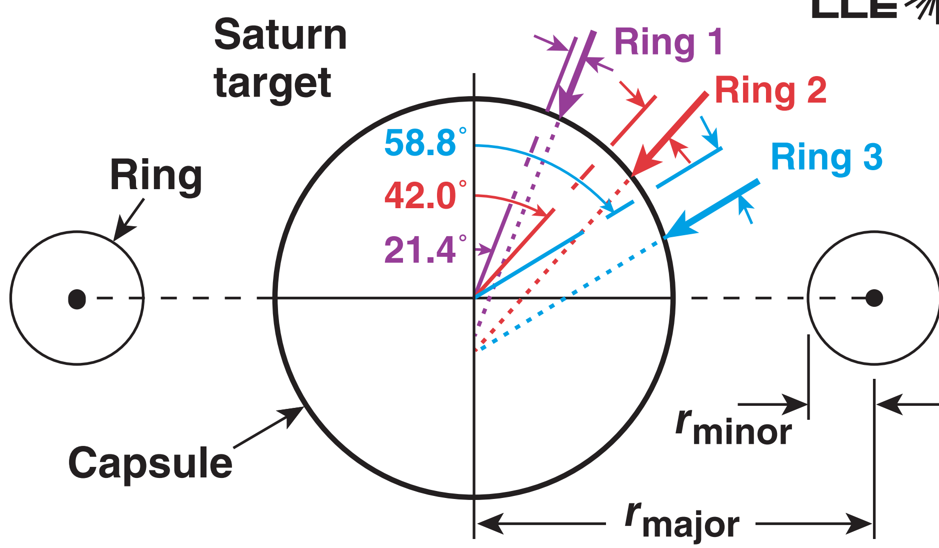


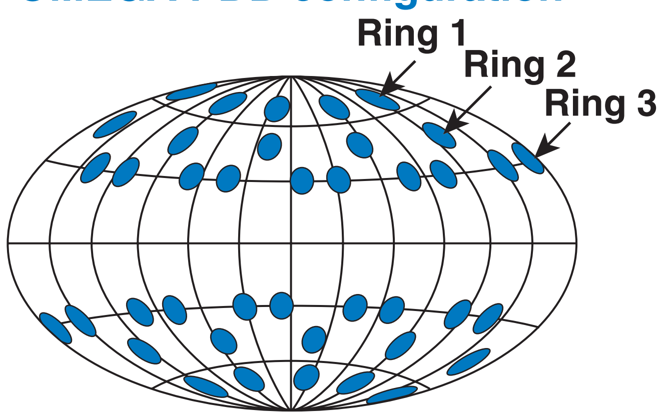
- Polar direct drive (PDD) is based on the optimization of phase-plate design, beam pointing, and pulse shaping.

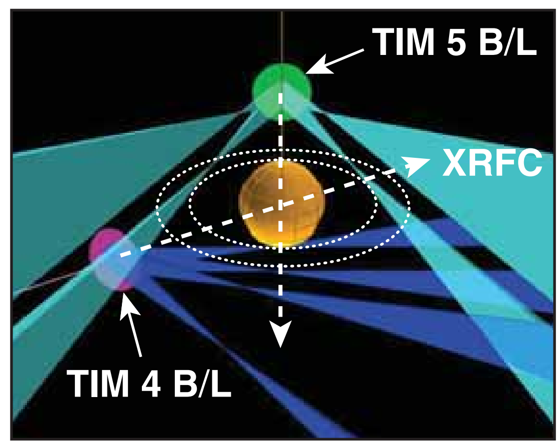
TC6631b

40 of the OMEGA beams are used to emulate the NIF 48 beam indirect-drive configuration









- The OMEGA beams, in six rings from 21° to 59°, are used to emulate the NIF geometry.

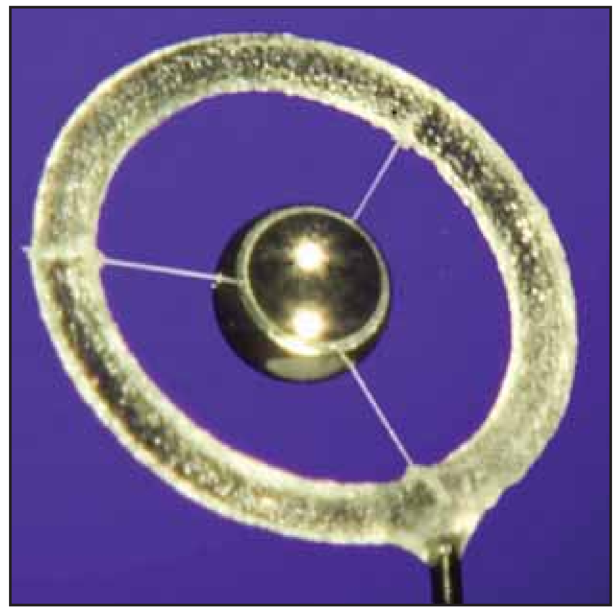
- Additional OMEGA beams are used for x-ray backlighting.

E14113

Two types of PDD target designs are being investigated: standard and Saturn

- Standard design

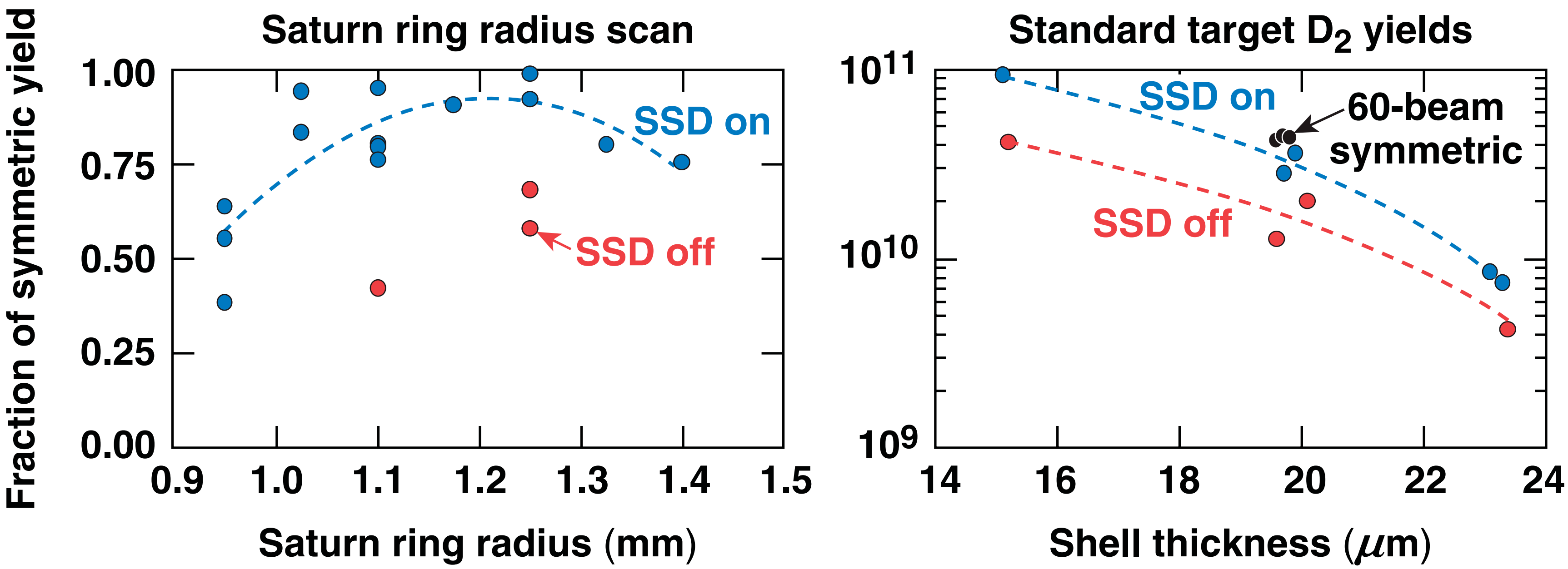
- Saturn design*
  - CH ring redirects laser energy toward the equator



*R. S. Craxton and D. Jacobs-Perkins, Phys. Rev. Lett. 94, 095002 (2005).
F. J. Marshall *et al.*, J. Phys. IV France 133, 153 (2006).
J. A. Marozas *et al.*, Phys. Plasmas 13, 056311 (2006).

TC7117a

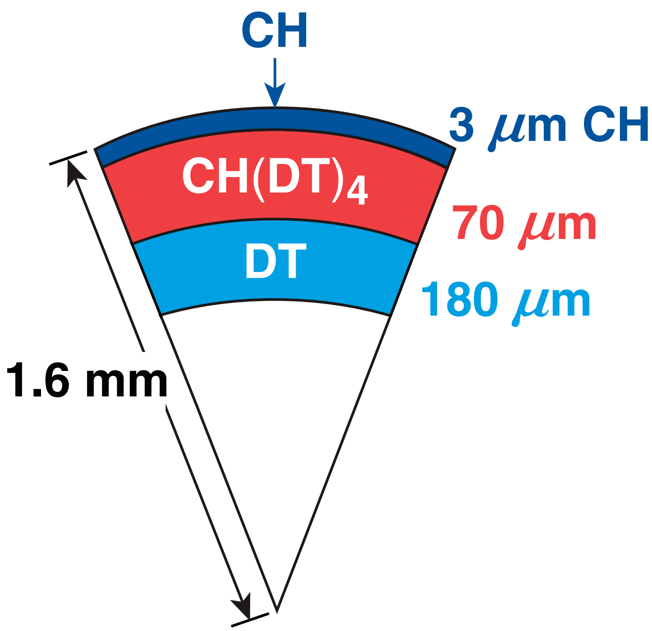
Polar-direct-drive (PDD) experiments on OMEGA have achieved near-symmetric-illumination yields

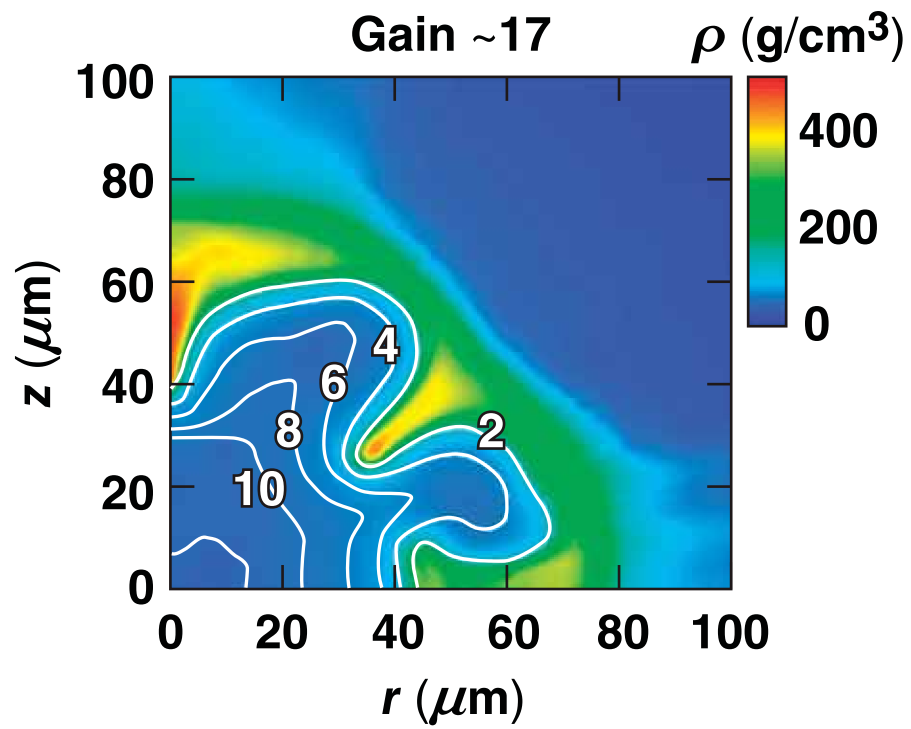


1-ns-square pulse, 15.3-kJ, 15-atm-D_2-filled CH shell implosions (including 60-beam symmetric)

E15162

2-D simulations including all sources of nonuniformity of a PDD wetted-foam NIF target ignites with a gain of ~17 at 1 MJ

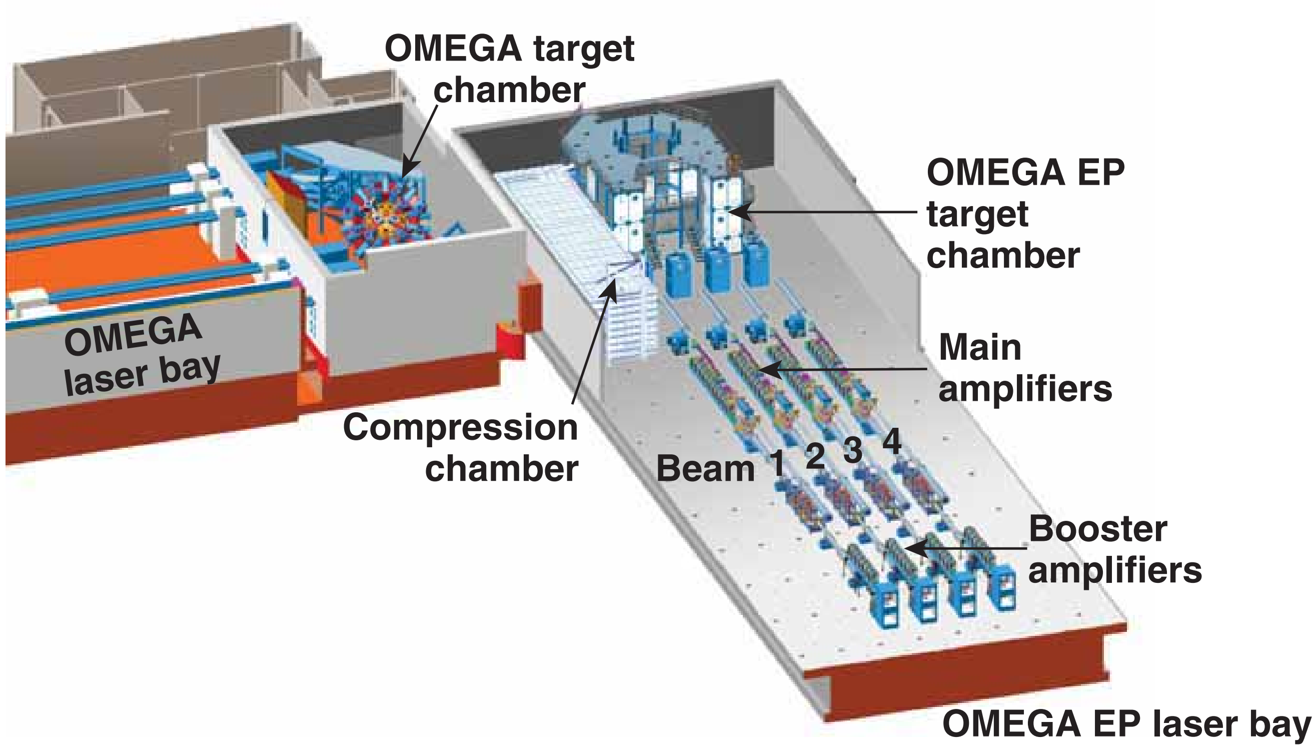




OMEGA EP

OMEGA EP Laser System will be used to backlight cryogenic implosions and explore fast ignition

UR LLE



Performance capabilities	Short-pulse Beam 1	Short-pulse Beam 2	Long pulse (any beam)	
Pulse width	1 to 100 ps	1 to 100 ps	1 ns	10 ns
Energy on target (kJ)	2.6 kJ, 10 to 100 ps grating limited <10 ps	2.6 kJ, 80- to 100-ps beam combiner limited <80 ps	2.5	6.5
Intensity (W/cm^2)	3×10^{20}	$\sim 2 \times 10^{18}$	3×10^{16}	8×10^{15}
Focusing (diam)	>80% in 20 μm	>80% in 40 μm	>80% in 100 μm	

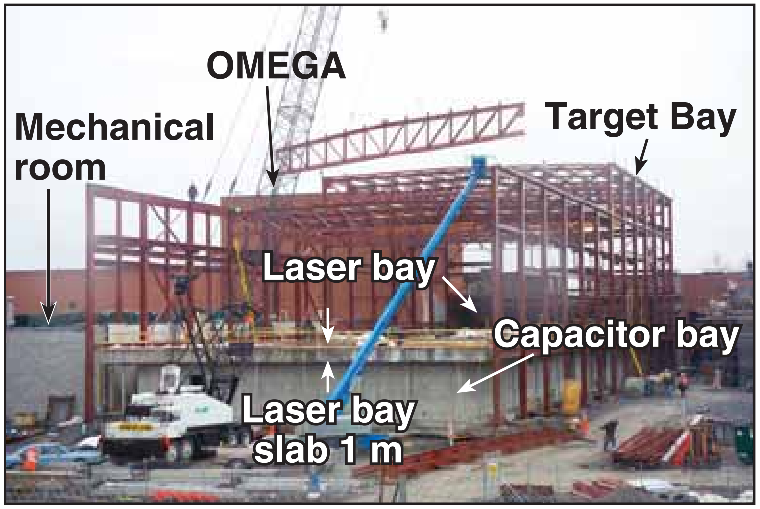
OMEGA EP will be completed in FY08

G6957n

OMEGA EP is on track for completion in April 2008

UR LLE

April 2004



January 2005

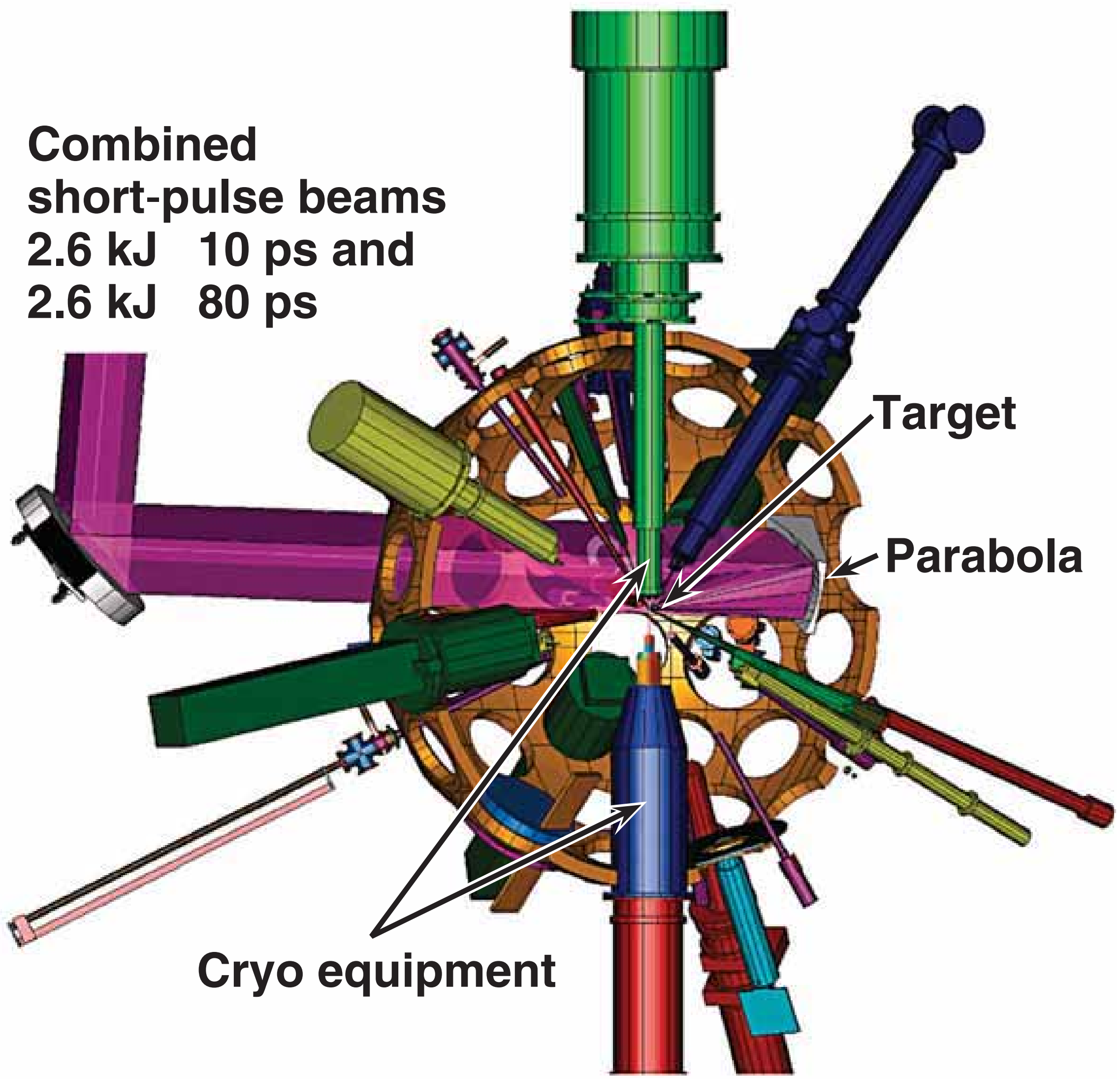
January 2006

March 2007

E13574g

The beams from OMEGA EP will be focused with a 23° *f*/2 off-axis parabola inside the OMEGA target chamber

- A fast-focusing optic is necessary to meet the 20-μm-diam focal-spot requirement.
- The size of the target chamber port limits the input beam size.
- The beam path has to stay clear of the cryogenic target handling equipment.



E13316b

Experimental capabilities for OMEGA EP beyond the original baseline are under development

- The OMEGA EP user workshop in January 2006 identified a number of desired capabilities.
  - a laser contrast diagnostic was identified to be a high-priority requirement
  - simultaneous side- and backlighting in the OMEGA EP target chamber is now part of the project baseline
  - a 4ω-probe beam is under development
  - a planar cryogenic target handling system is being designed
  - a number of new target diagnostics were proposed and development has started on some of them
- A second OMEGA EP user workshop is planned for 30 May—1 June 2007 to start the detailed development of experimental campaigns.

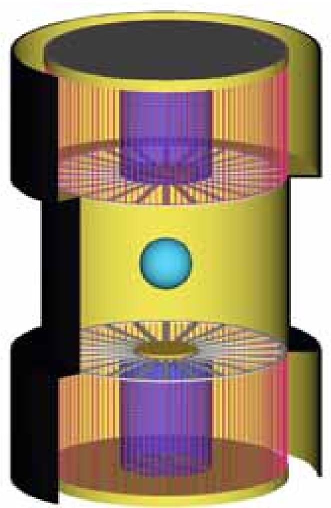
User experiments on OMEGA EP will start in FY09

Summary/Conclusions

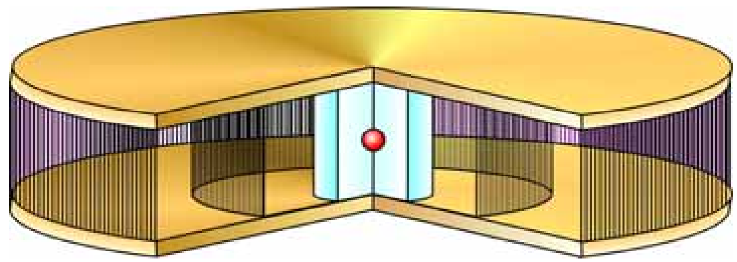
The Laboratory for Laser Energetics validates ICF ignition concepts

- The baseline direct-drive ignition target for the NIF is a thick cryogenic DT shell enclosed by a thin plastic shell.
- DT ice-layer roughness <1-μm rms are routinely achieved and cryogenic D_2 and DT implosions are ongoing.
- Polar direct drive (PDD) will allow direct-drive ignition experiments while NIF is configured for indirect drive.
- OMEGA provides critical data for indirect-drive ignition (IDI).
- OMEGA EP (high energy petawatt) will be completed in April 2008 and integrated fast-ignition experiments will begin in 2009.

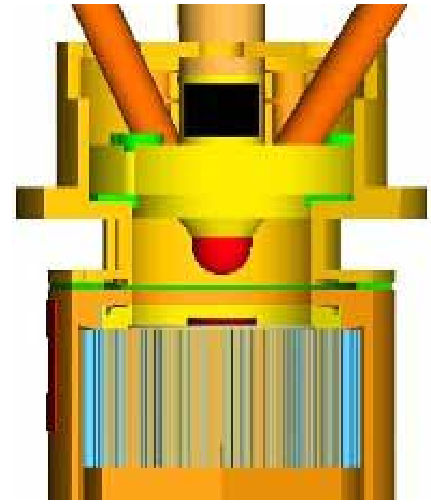
Existing and near-term ICF/HEDP capabilities relevant to IFE



Double-ended Hohlraum



Dynamic Hohlraum



Advanced Concepts (e.g. Fast Ignition)

IFE Science and Technology San Ramon, CA April 25, 2007	M. Keith Matzen Sandia National Laboratories Albuquerque, New Mexico USA

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

- What are the HEDP questions that can be addressed in the near-term that are relevant to IFE?
- How can NNSA facilities be used to support IFE?
- What are current or planned or planned interactions with other communities?
- Who are the customers for this HEDP science besides the IFE/ICF community?

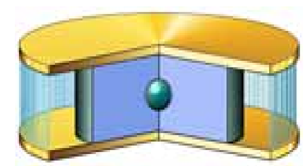
Recent Results in Z-IFE

1. RTLs

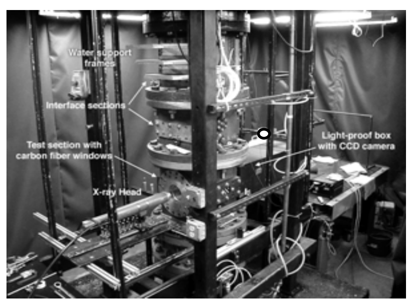
4. Z-PoP planning

2. LTD repetitive driver

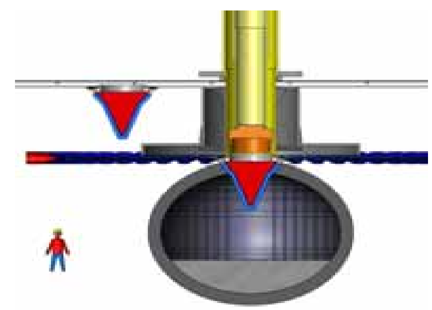
5. Z-IFE targets for GJ yields



3. Shock mitigation



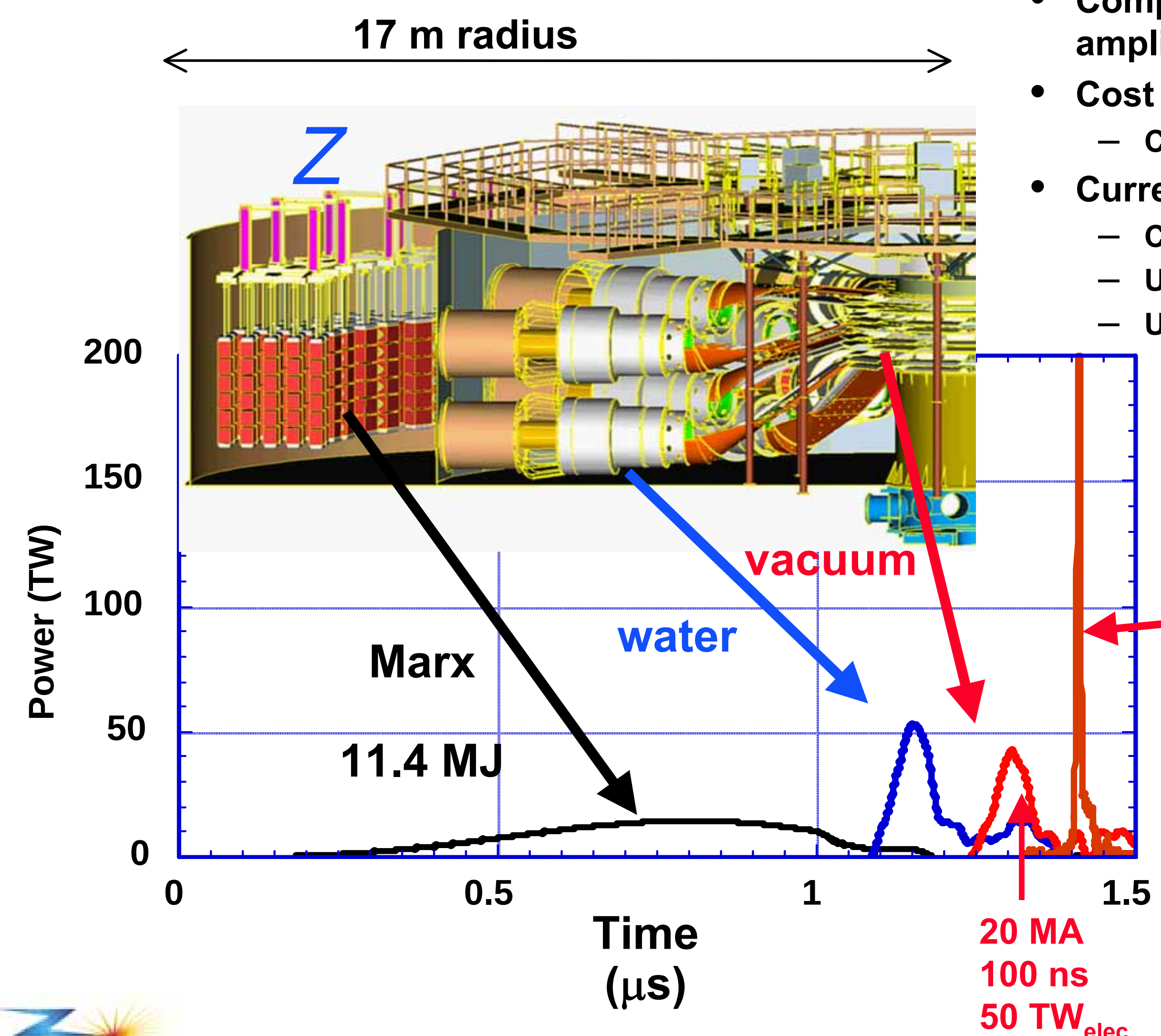
6. Z-IFE power Plant



Sandia's Pulsed Power facilities provide experimental platforms for high energy density science

- Capabilities
  - Large scale computations
  - Theory
  - Diagnostics
  - Precision measurements
- Large-scale experimental facilities
  - Pulsed power facility (Z): 26 MA, 100 TW_e, 100 ns (up to 350 ns)
  - Laser facility (Z-Beamlet, Z-Petawatt): 2 TW, 4 PW (ns, ps; multi-kJ)
- Applications
  - Magnetically-driven plasma implosions
  - Magnetically-driven compression waves and flyer plate acceleration
  - High voltage breakdown phenomenology and electrostatic discharge

Laboratory ICF is a challenging problem: a combination of pulsed power and lasers provide risk mitigation and diversification



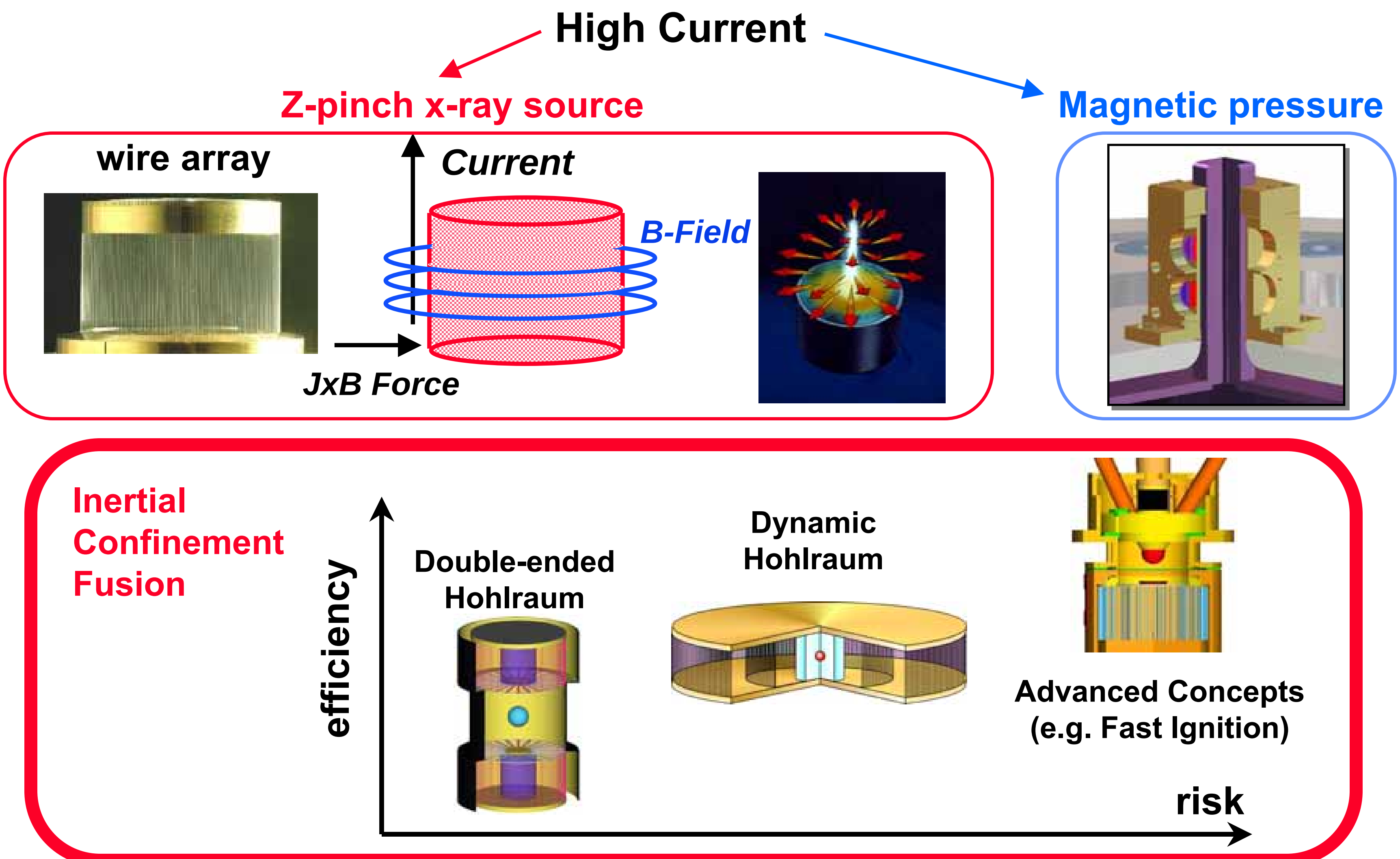
- Compact, efficient, power amplification
- Cost effective
  - Capital and operating
- Current/magnetic fields
  - Complementary for many expts
  - Unique for pinches, ICE, and flyers
  - Unique for energy
    - Efficiency, rep-rate
    - Stand-off
    - Chamber protection
    - Target injection and tracking

x ray output
~1.6 MJ
~200 TW

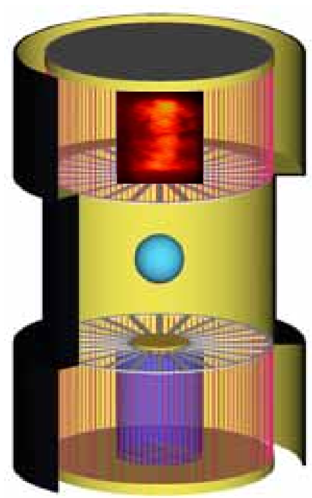
Electrical to x-ray energy

Conversion efficiency ~ 15%

High current pulsed power accelerators drive many different load configurations



Ongoing design work and 6 years of validation experiments give confidence that the z-pinch double-ended hohlraum (DEH) can meet the requirements for ICF

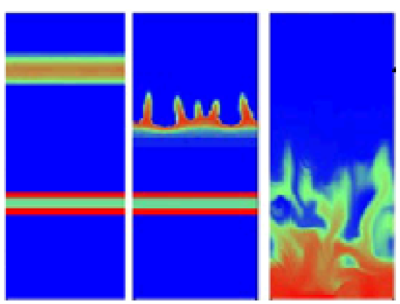


PHYSICS OF PLASMAS VOLUME 6, NUMBER 5 MAY 1999

High yield inertial confinement fusion target design for a *z*-pinch-driven hohlraum*

James H. Hammer,† Max Tabak, Scott C. Wilks, John D. Lindl, David S. Bailey, Peter W. Rambo, Arthur Toor, and George B. Zimmerman
Lawrence Livermore National Laboratory, Livermore, California 94551

John L. Porter, Jr.
Sandia National Laboratories, Albuquerque, New Mexico 87185-1191

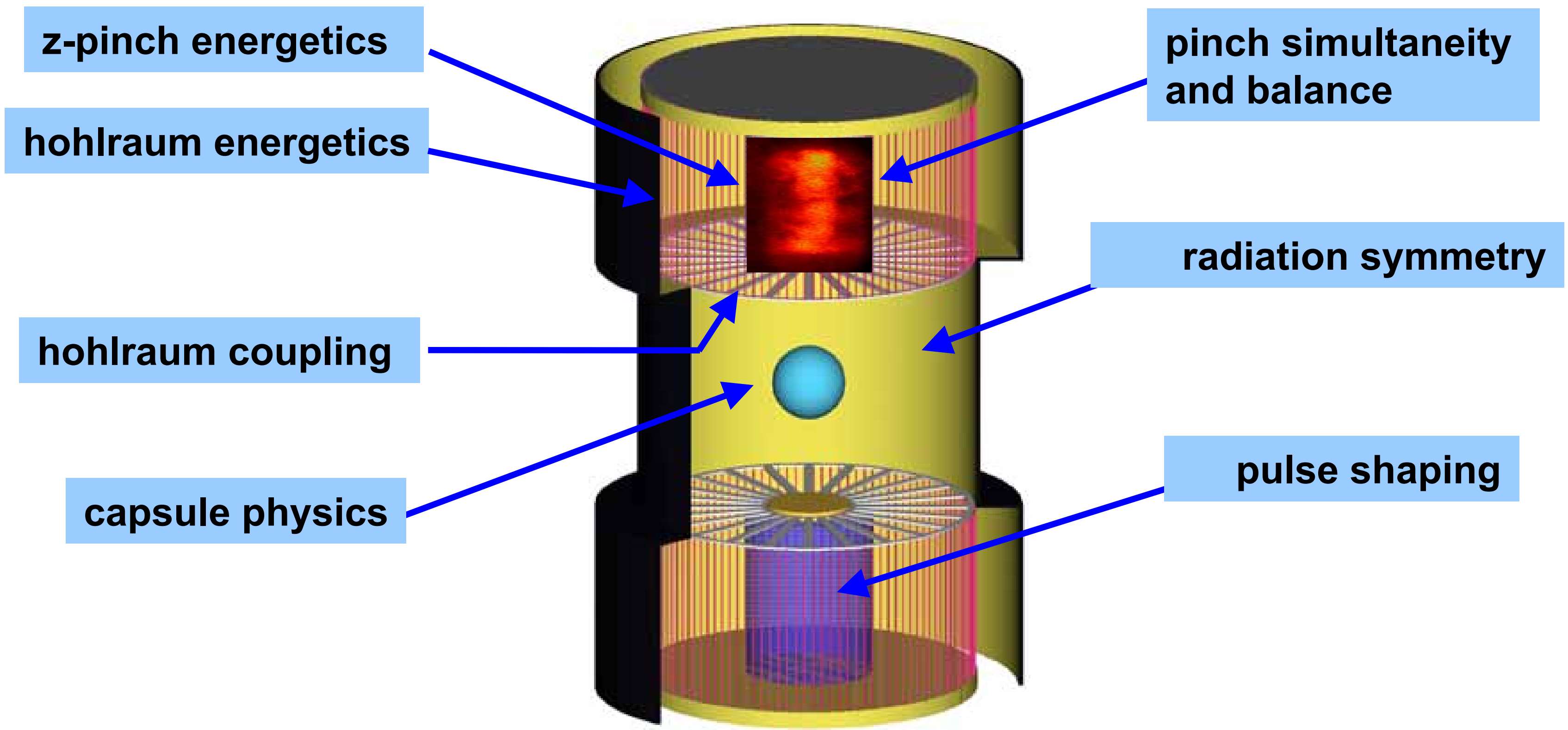


Key results of initial scoping study:

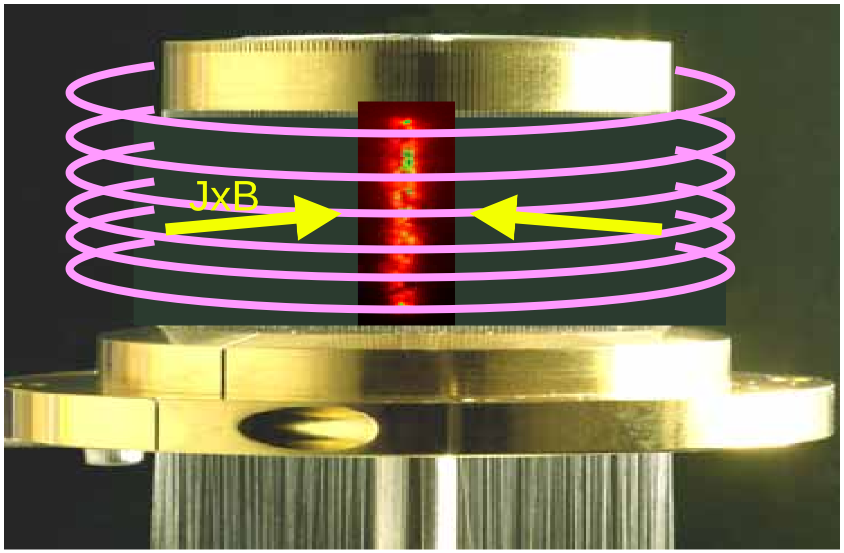
- **500 MJ yield capsule with robustness similar to NIF**
- **16 MJ total x-ray energy output from 2 pinches**
- **2 x 62 MA currents required with 100 ns rise time**
- **Pulse shaping via multi-shell z-pinch load design**
- **Spoke x-ray transmission of > 60% required**
- **Pinch power balance of 7% required**

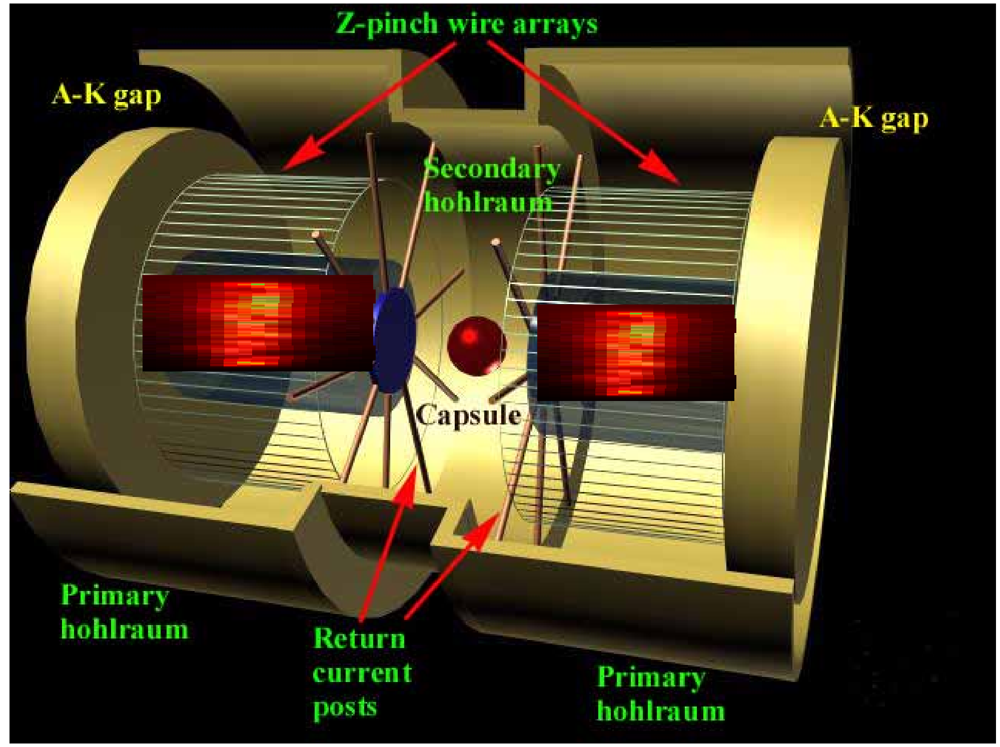
The issues identified have been the focus of simulation and experiment

The double-ended-hohlraum (DEH) high yield concept separates capsule and z-pinch physics issues



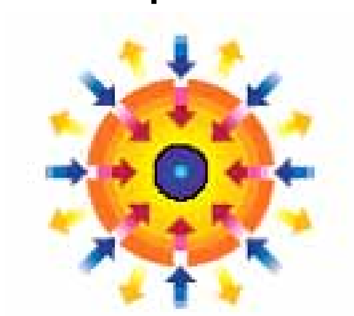
Achieving inertial confinement fusion in the laboratory is a grand scientific and engineering challenge



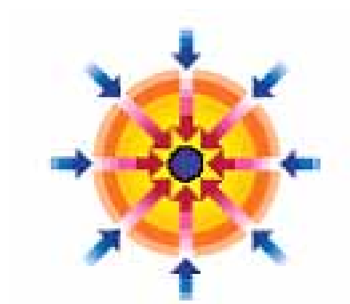


Target heating

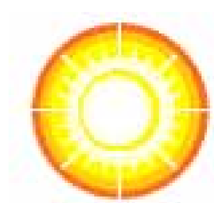
Compression



Ignition



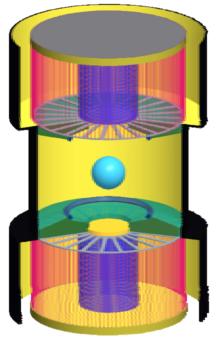
Burn



We have developed a modern high-yield target design for the z-pinch-driven double-ended hohlraum

J. Hammer, M. Tabak, S. Wilks, *et al., Phys. Plasmas* **6**, 2129 (1999)

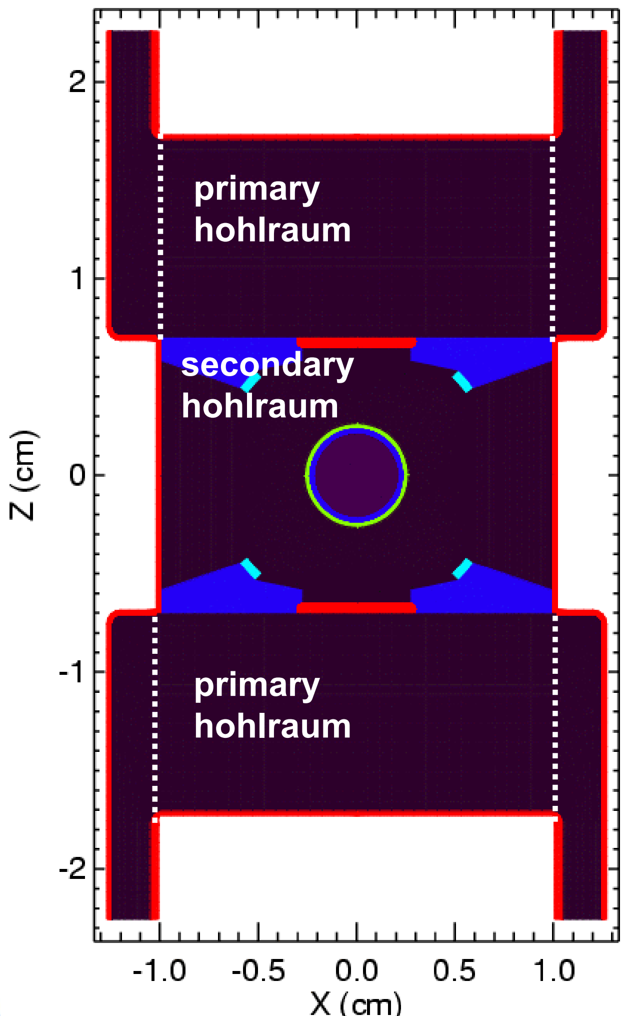
R. A. Vesey, M. C. Herrmann, R. W. Lemke et al., *Phys. Plasmas* **14**, 056302 *(*2007)

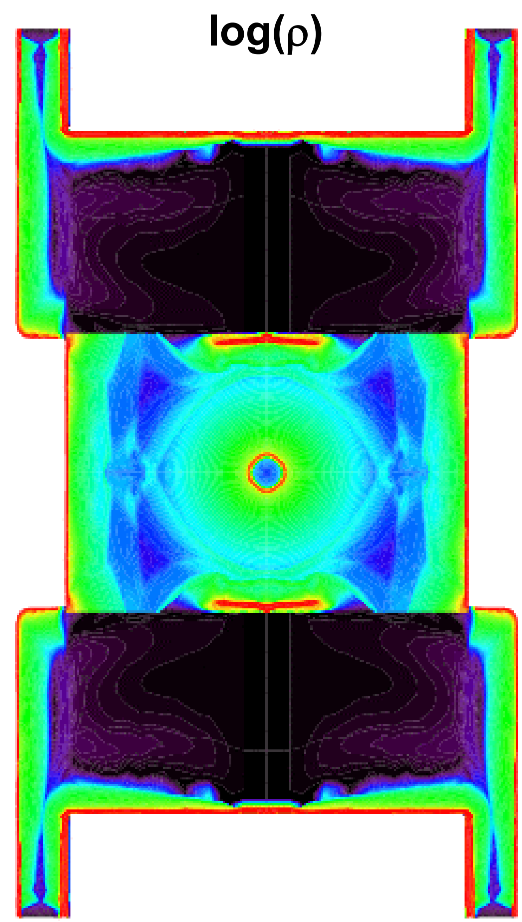


- **Demonstrated ignition in 2D LASNEX hohlraum+capsule simulations for the first time**
- **Developed strategy to control time-dependent hohlraum symmetry**
- **Robustness of 220 eV capsules is suitable for z-pinch driven hohlraum**
- **Defining Z-pinch and accelerator requirements based on the capsule and hohlraum requirements**
- **Extending target design work to smaller scale vacuum hohlraums including advanced compact x-ray sources**

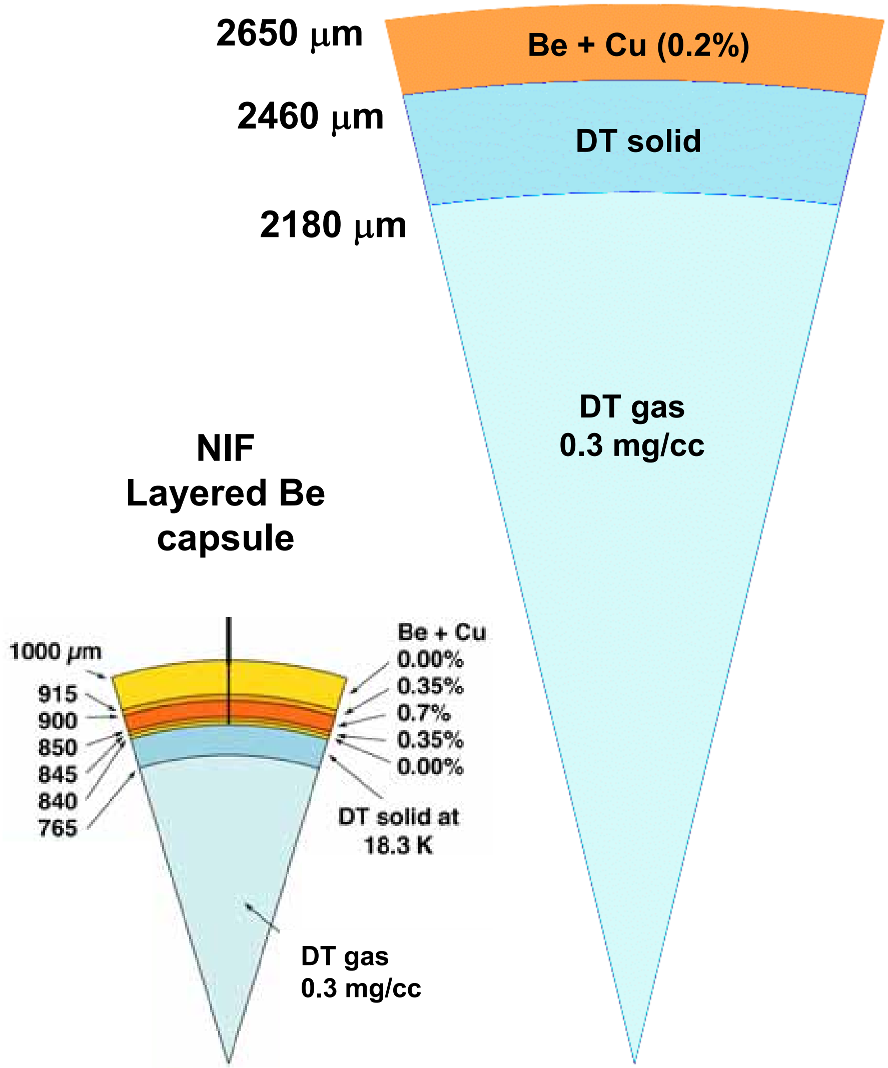
Sandia National Laboratories

2D LASNEX hohlraum + capsule simulations capture the essential physics of radiation coupling and symmetry





The current high yield target design centers around a beryllium ablator capsule with 500 MJ fusion yield



1D capsule parameters

Capsule	NIF Rev1[1]	DEH capsule
Ablator outer radius (mm)	1.0	2.65
Peak drive temperature (eV)	300	220
Ablator thickness (μm)	160	190
DT fuel thickness (μm)	75	280
DT fuel mass (mg)	0.15	4.74
Absorbed energy (MJ)	0.14	1.21
Yield (MJ)	13	520
Peak ρr (g/cm^2)	1.9	3.1
Implosion velocity (cm/μs)	36.4	26.0
Fuel KE margin	33%	29%
Hot spot convergence ratio	36	34

[1]NIF ignition point design layered Be capsule Rev 1

We are developing new pulsed power architectures for a next generation z-pinch facility

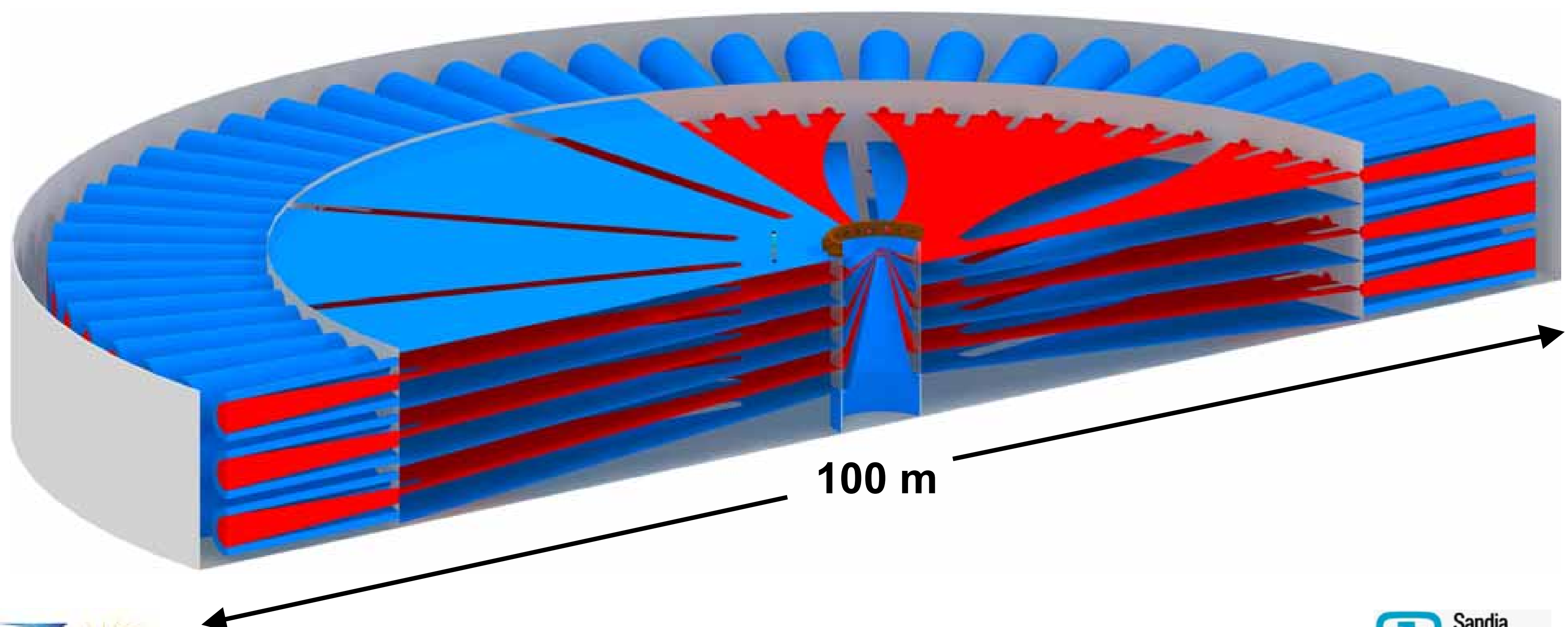
$E_{stored} = 180\ \mathrm{MJ}$ $V = 24\ \mathrm{MV}$

$P_{electrical} = 1100\ \mathrm{TW}$ $I = 68\ \mathrm{MA}$

$L = 29\ \mathrm{nH}$ $\tau_{implosion} = 95\ \mathrm{ns}$

$\eta_{electrical} = 70\%$ diameter = 100 m

W. A. Stygar, *et. al*., "Architecture of petawatt-class z-pinch drivers", Phys. Rev. ST Accel. Beams 10, 03040 (2007)



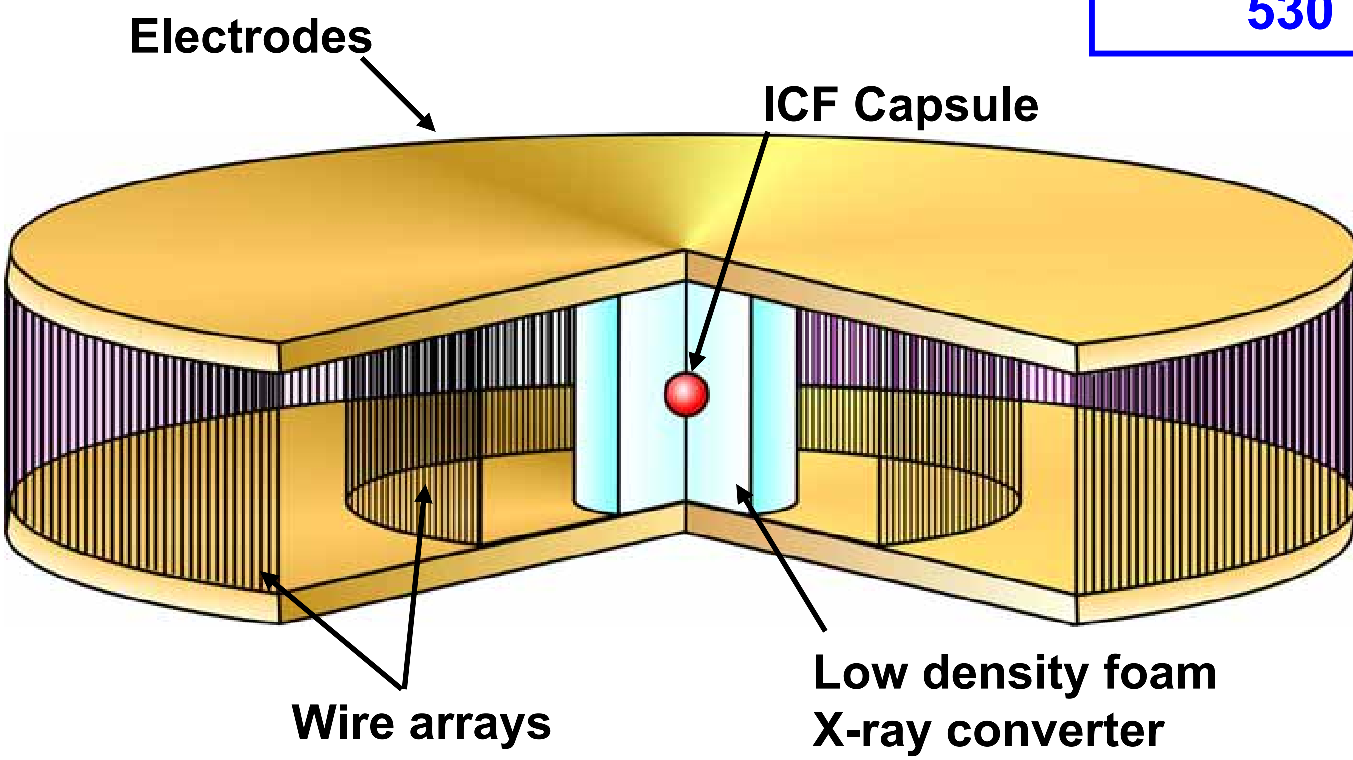
Recent Publications

Recent Publications Relevant to the Double Z-Pinch Target Design :

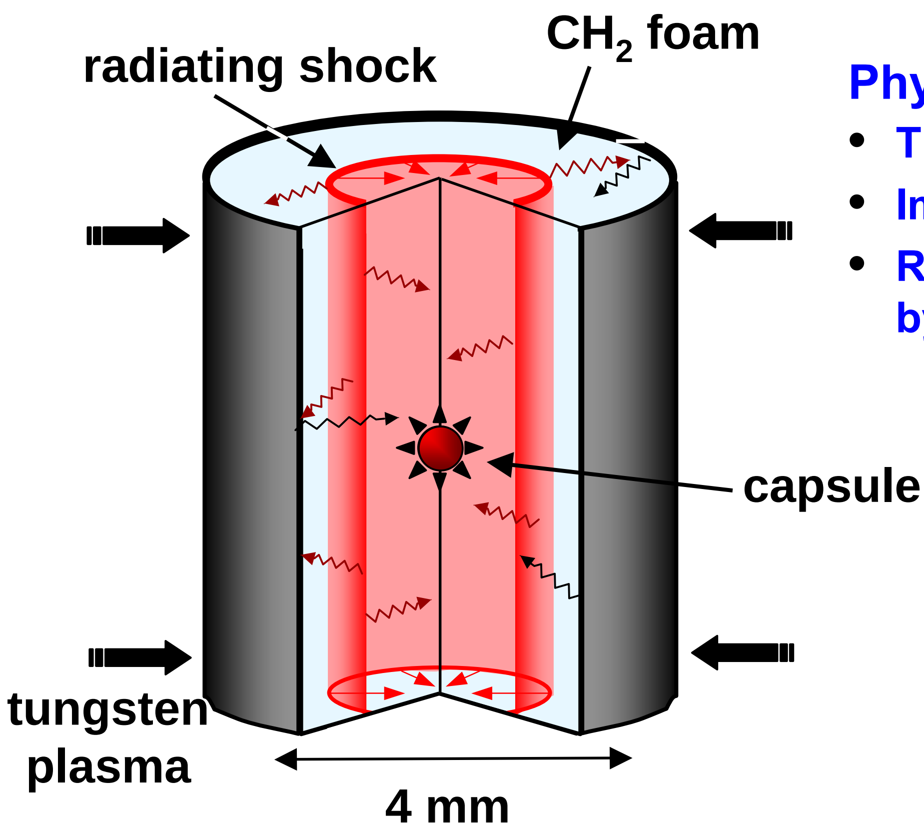
D. B. Sinars et al., *Phys. Plasmas* **12**, 056303 (2005) -- Wire array radiography
M. E. Cuneo et al., *Phys. Rev. E* **71**, 046406 (2005) -- Wire array trajectories
W. A. Stygar et al., *Phys. Rev. E* **72**, 026404 (2005) -- High yield system scaling
M. E. Cuneo et al., *Phys. Rev. Lett.* **95**, 185001 (2005) -- Z-pinch pulse shaping experiments
M. E. Cuneo et al., *Plasma Phys. Control. Fusion* **48**, R1 (2006) -- Concept review
R. A. Vesey et al., *J. Phys. IV France* **133**, 1167 (2006) -- 2D hohlraum model validation
M. E. Cuneo et al., *Phys. Plasmas* **13**, 056318 (2006) -- Nested wire array dynamics
R. A. Vesey et al., *Phys. Plasmas* **14**, 056302 (2007) -- 500 MJ high yield target design
W. A. Stygar et al., *Phys. Rev. ST Accel. Beams* **10**, 030401 (2007) -- Accelerator architecture

High temperature capsule implosions are performed in the "Dynamic Hohlraum" configuration

High yield design
54 MA
530 MJ



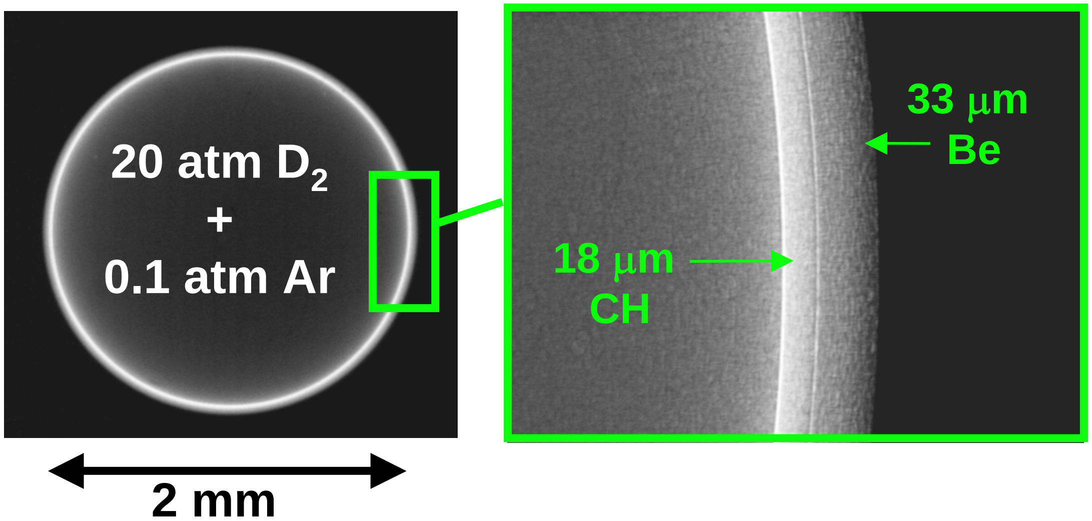
A radiating shock heats the dynamic hohlraum

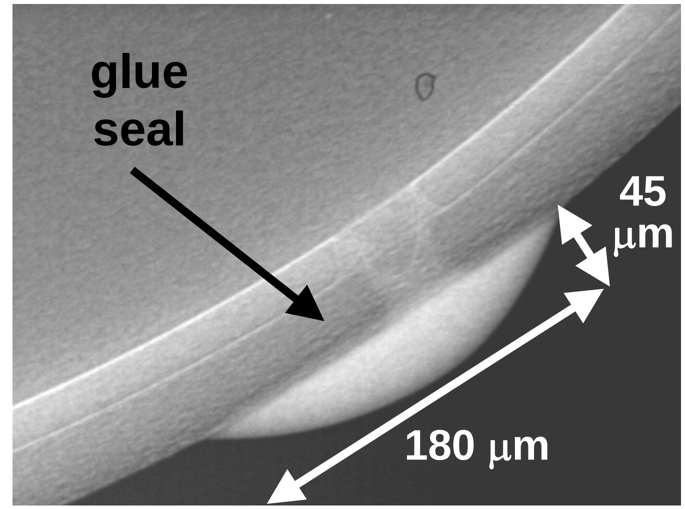


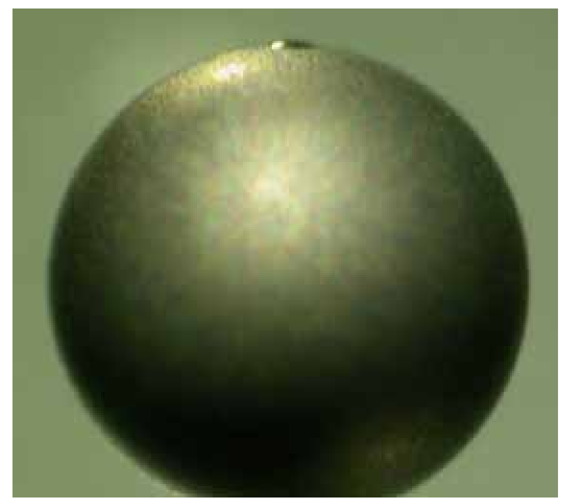
Physics of the Dynamic Hohlraum
- Tungsten Z-pinch plasma impacts foam
- Impact launches radiating shocks
- Radiation is trapped and symmetrized by the tungsten plasma

Measurements to validate simulations
- Shock velocity
- "Dante" equivalent temperatures
- Hohlraum tracer spectra
- Capsule implosion trajectory
- Implosion core T_e, n_e
- Neutron yield

Be/CH capsules have been fabricated for first-step evaluation of x-ray driven Be implosions







Significance: Be is the ablator of choice for many ignition and high yield designs, yet experimental validation of the anticipated benefits are lacking

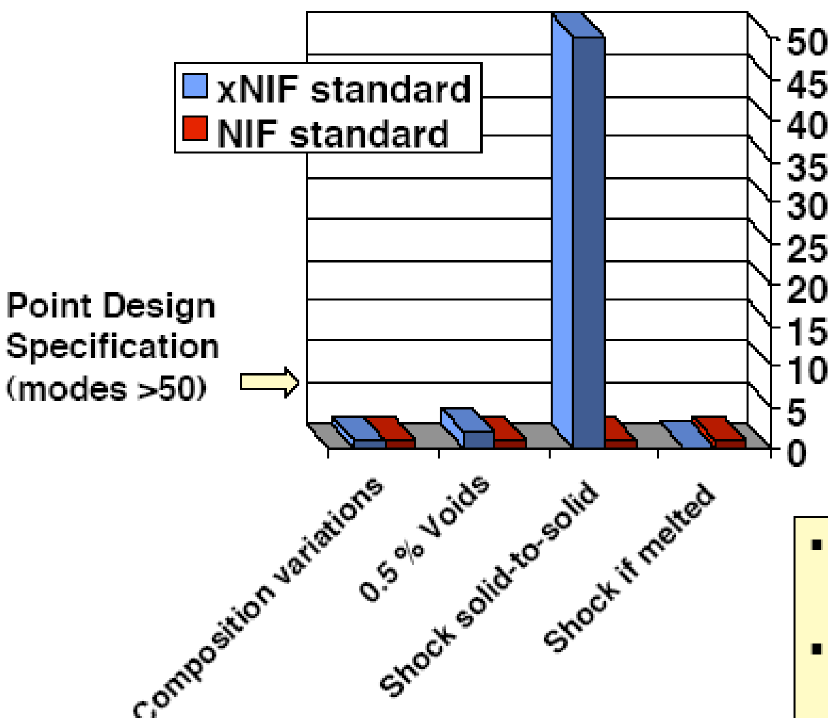
Be capsules produced record neutron yields (~ 3.5×10^{11})

We are investigating the shock melting of Be as part of the National Ignition Campaign

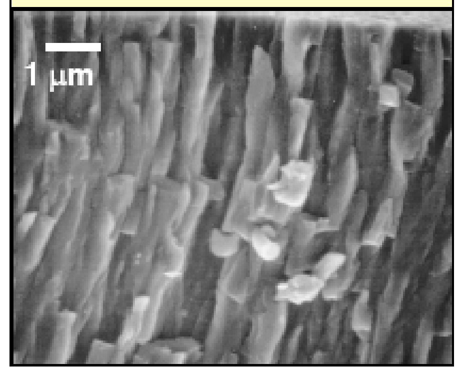
Initial calculations indicate that melting the beryllium is the key to minimizing beryllium microstructure effects

The National Ignition Facility

(Results from ALE3D calculations and analytic estimates



Sputter deposited Be has submicron grains



- The first shock in the ignition point design target melts the Be
- We are developing experiments to measure the melt conditions and residual perturbations on Omega and Z experiments

From John Lindl's presentation at the JASON's review

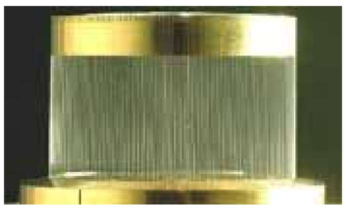
Sandia National Laboratories

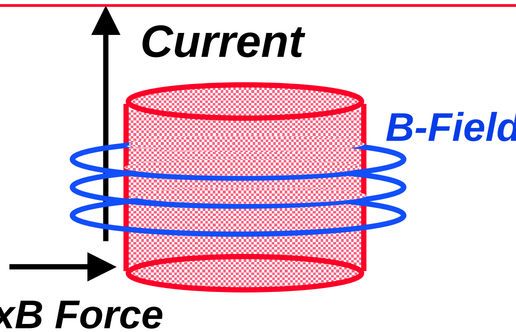
High current pulsed power accelerators drive many different load configurations

High Current

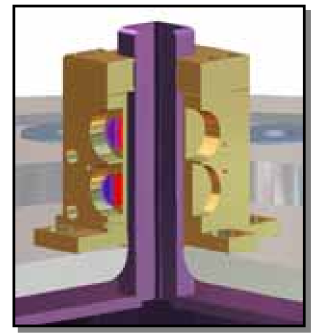
Z-pinch x-ray source

wire array

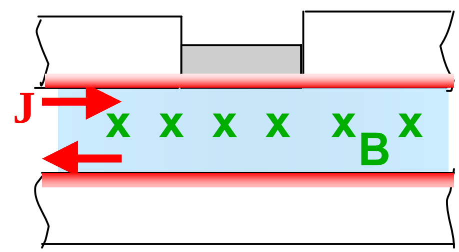




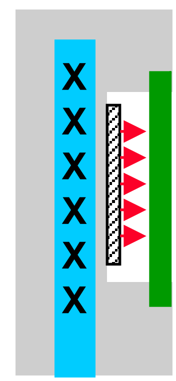
Magnetic pressure



- **Shaping the current pulse enabled:**
  - Flyer plates to velocities of 34 km/s
    - Deuterium EOS to 1.8 Mbar
    - High-Z Hugoniot expts to > 20 Mbar
  - Isentropic Compression Experiments
    - Off-Hugoniot EOS measurements to 4 Mbar
    - Al strength measurements to 2.4 Mbar
    - Solid-solid and liquid-solid phase transitions



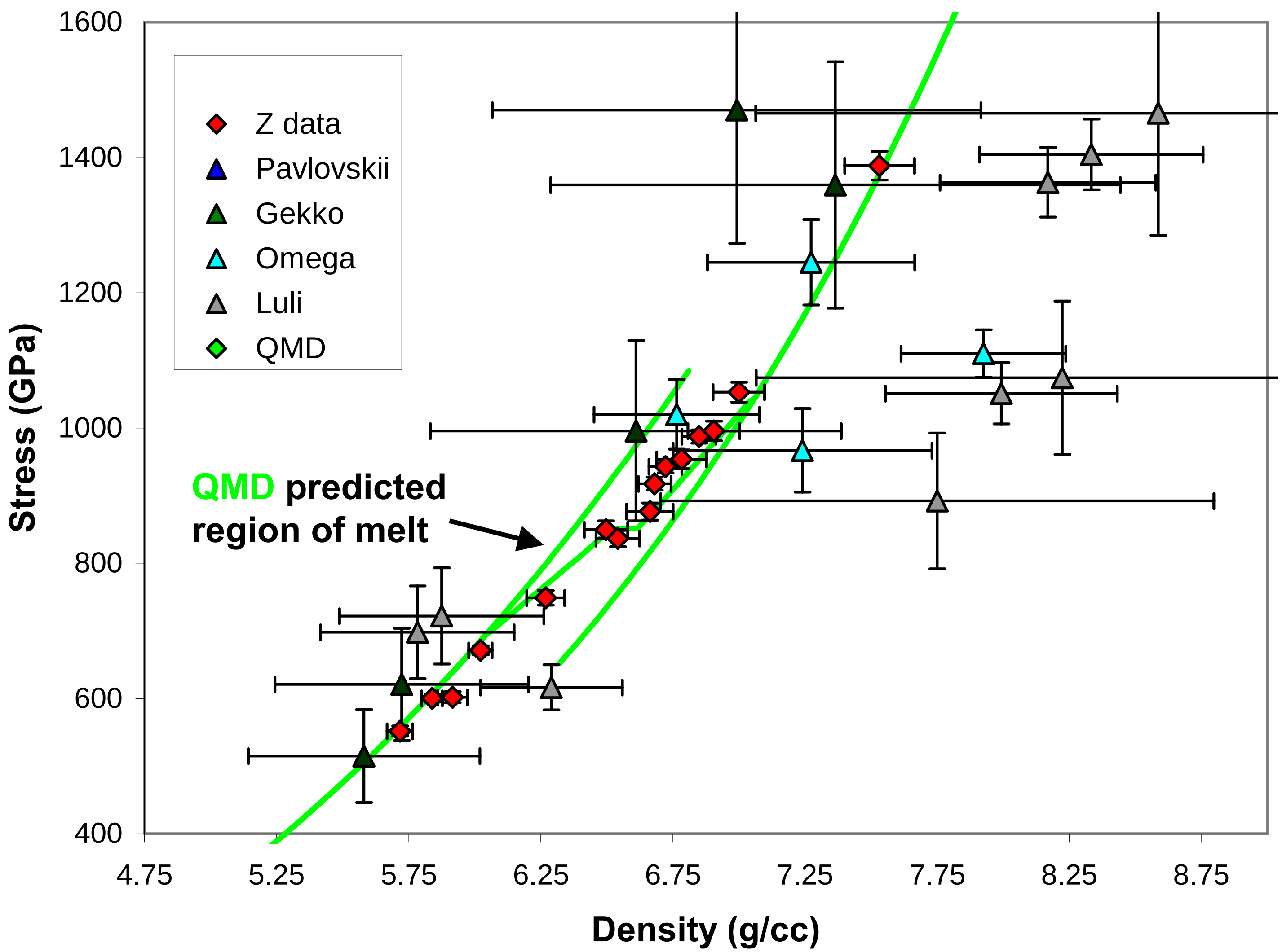
Isentropic Compression



Flyer Plate

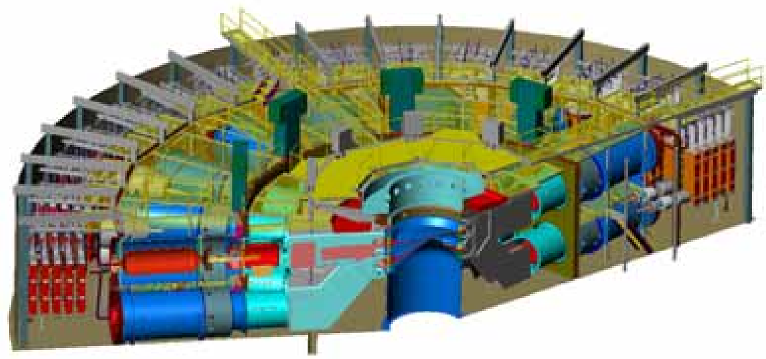
Z answered important questions about the properties of Be and diamond for the National Ignition Campaign

stress versus density for diamond



- **The Z data was obtained in 1 week**
- **Measurements on Z have a uncertainty of ≤ 1%**

Major upgrades of Z and Z-Beamlet are underway



- The Z-Refurbishment project is upgrading the performance of Z
  - 18 MA to 26 MA
  - 2x increase in diagnostic access
  - 2x shot rate capability

- The Z-Petawatt project is upgrading the capability of Z-Beamlet
  - 2 TW to 1 PW
  - backlighter hν 9 - 25 keV
  - integrated FI experiments on ZR

The ZR and Z-Petawatt facilities will begin operations in 2007

Z provides unique and complementary experimental capabilities

Unique Capabilities

Z

- Magnetically-driven implosions
- Highest precision isentropic compression experiment (ICE) EOS
- Radiation effects testing
- Alternative fusion concepts

NIF

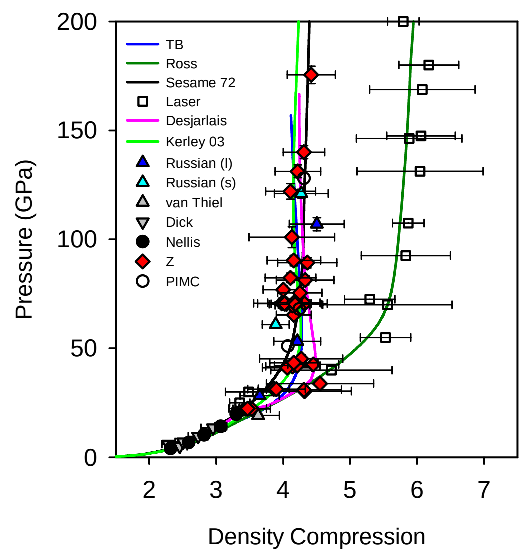
- Hot spot ignition and burn
- Highest temperatures
- Highest pressures

Omega/Omega EP

- Direct-drive ICF target physics
- Fast ignition proof-of-principle

Complementary Capabilities

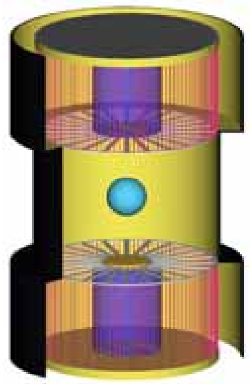
- Radiation flow
- Radiation hydrodynamics
- Instability and mix
- Opacity
- Equation of state
- ICF target physics

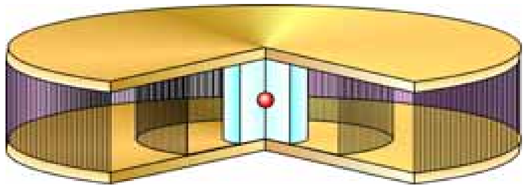


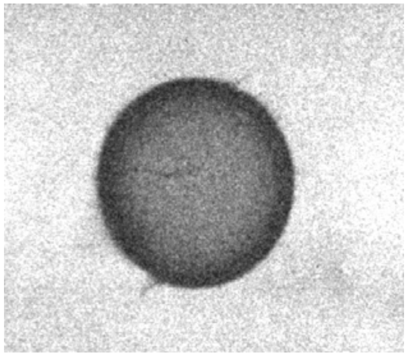
Cost, availability, diagnostics, reproducibility, precision, and flexibility ultimately will determine which facilities are used for specific experiments

Summary

- **Double-ended hohlraum**
  - Simulations and experiments are addressing the key issues identified in the Z-DEH
  - 2D Lasnex hohlraum / capsule simulations have demonstrated time-dependent symmetry control, ignition and burn of 500 MJ capsule with a source x-ray energy of 18 MJ
- **Dynamic hohlraum**
  - Be capsule implosions have produced record D-D yields
  - Performing tomographic reconstruction of the 2D T_e and n_e spatial profiles
- **National Ignition Campaign**
  - Measurements of Be and diamond melt
  - Measurements of fill-tube hydro







Nike:

ICF experiments & IFE Physics issues

IFE Science & Technology Workshop

Andy Schmitt
Plasma Physics Division
Naval Research Laboratory
...on behalf of many others
at Nike & NRL

Physics Issues for Direct Drive IFE

Coupling & Laser Plasma Instabilties (LPI)

Hydro Stability

Modelling & Simulation

Symmetry & Coupling issues have been mitigated or solved with the KrF laser

NRL

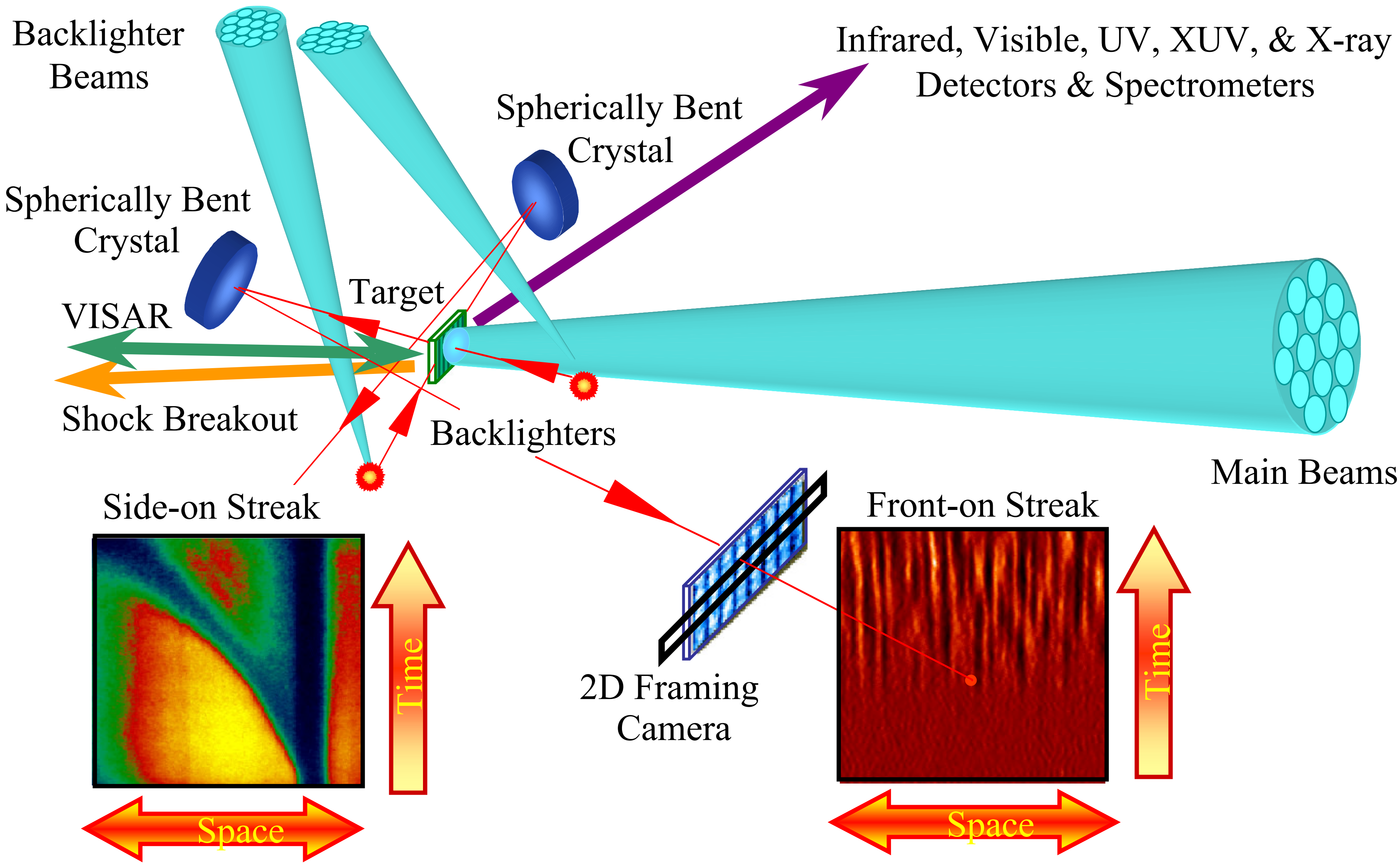
KrF strengths:
• smallest wavelength of the leading brand high-power lasers
• largest usable bandwidth
• most uniform focal profile achieved

• Short laser wavelength penetrates deeper into target, increasing absorption, mass ablation, and coupling while reducing risk of LPI.

• Large bandwidth and image-relaying design makes optical smoothing, focal spot control relatively easy

• Zooming the laser spot allows more control of symmetry and can significantly increase coupling efficiency

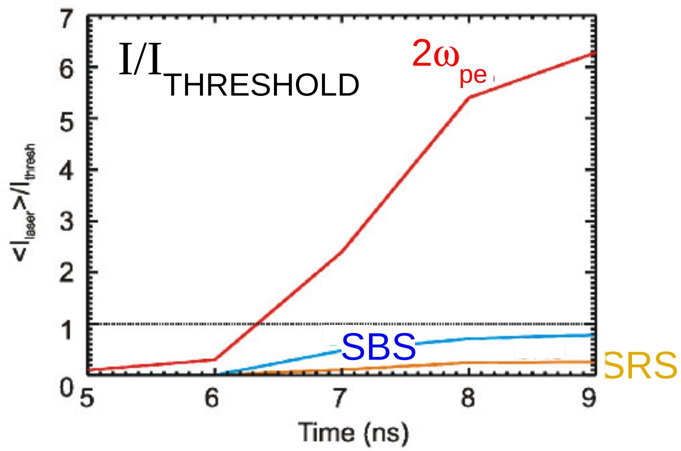
Nike experimental configuration and capability



LPI: Unlike indirect-drive, the two-plasmon decay ($2\omega_{pe}$) instability is the most worrisome for direct-drive

"The $2\omega_{pe}$ instability is typically over threshold in direct-drive targets, while SBS and SRS are marginal or below threshold."

This ignores the (considerable) effect of optical smoothing and assumes use of the average laser intensity.



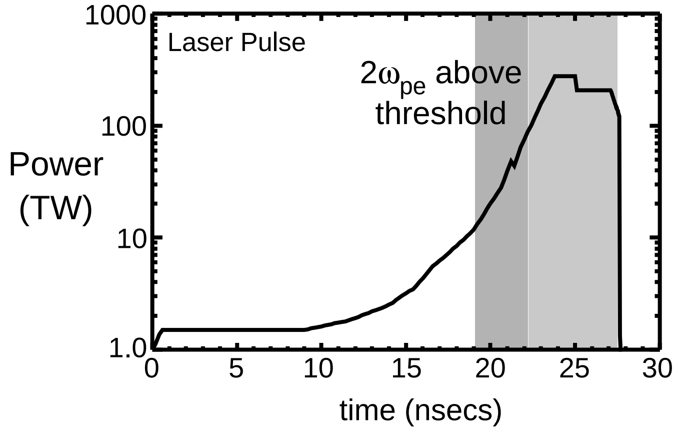
$$I_{2\omega_p} > 0.216\, T_e / L_n$$

$$I_{SBS} > 0.68\, T_e \Big/ \left[\frac{n}{n_c} L_v \right]$$

$$I_{SRS} > 16/L_n$$

Caveats:

- instantaneous maximum intensity is ~ $5I_{avg}$
- Experimentally, optical smoothing can suppress or reduce all these instabilities.
- $2\omega_{pe}$: theoretically, most unstable modes in hot spots should be tamed by transverse localization.
- $2\omega_{pe}$: higher temperatures later (Te>3keV) can also suppress it via Landau damping.

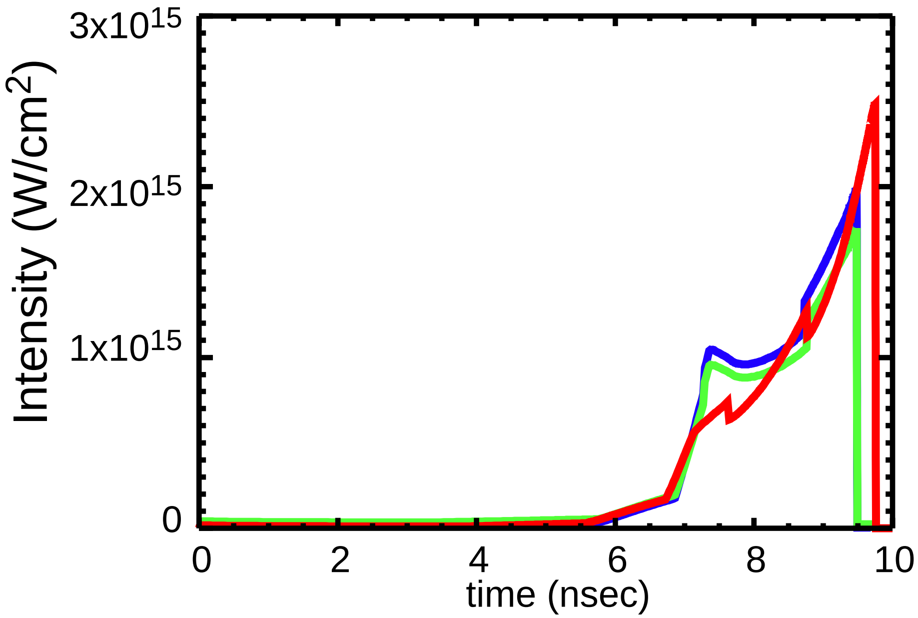


B. Afeyan contr. to J. Weaver et al., APS/Div. Plasma Phys. Conf. 2006

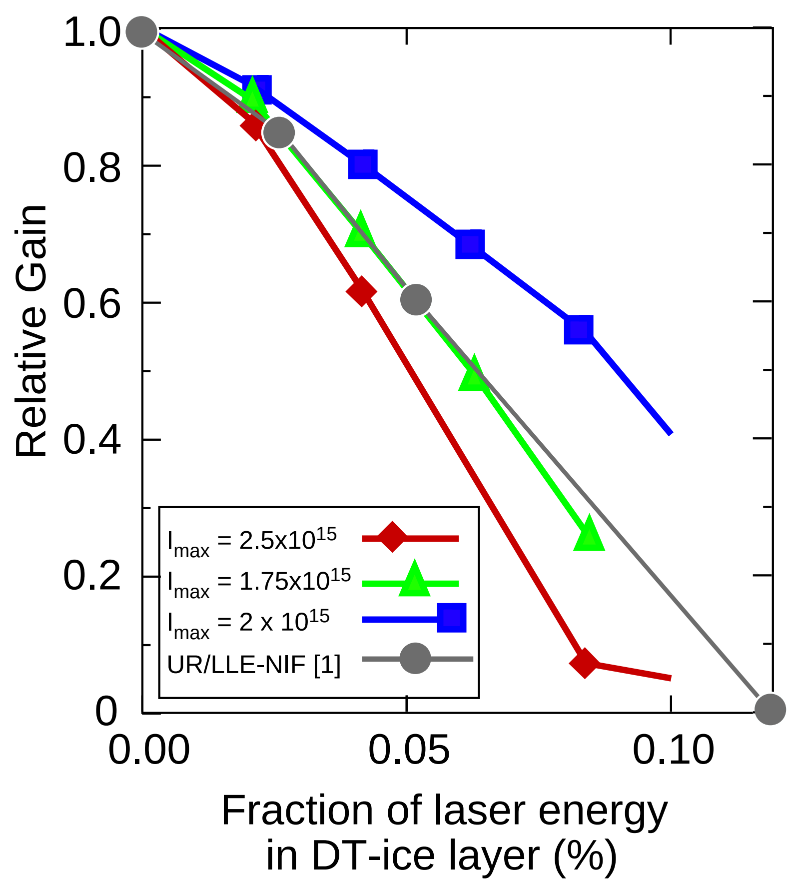
Why worry about $2\omega_{pe}$? Fast electrons

- Using a simple "optically thin" electron deposition model, we estimate target sensitivity

- hot electron production is proportional to intensity for t $\geq$ 6.5 ns ($I > 10^{14}$ W/cm^2)



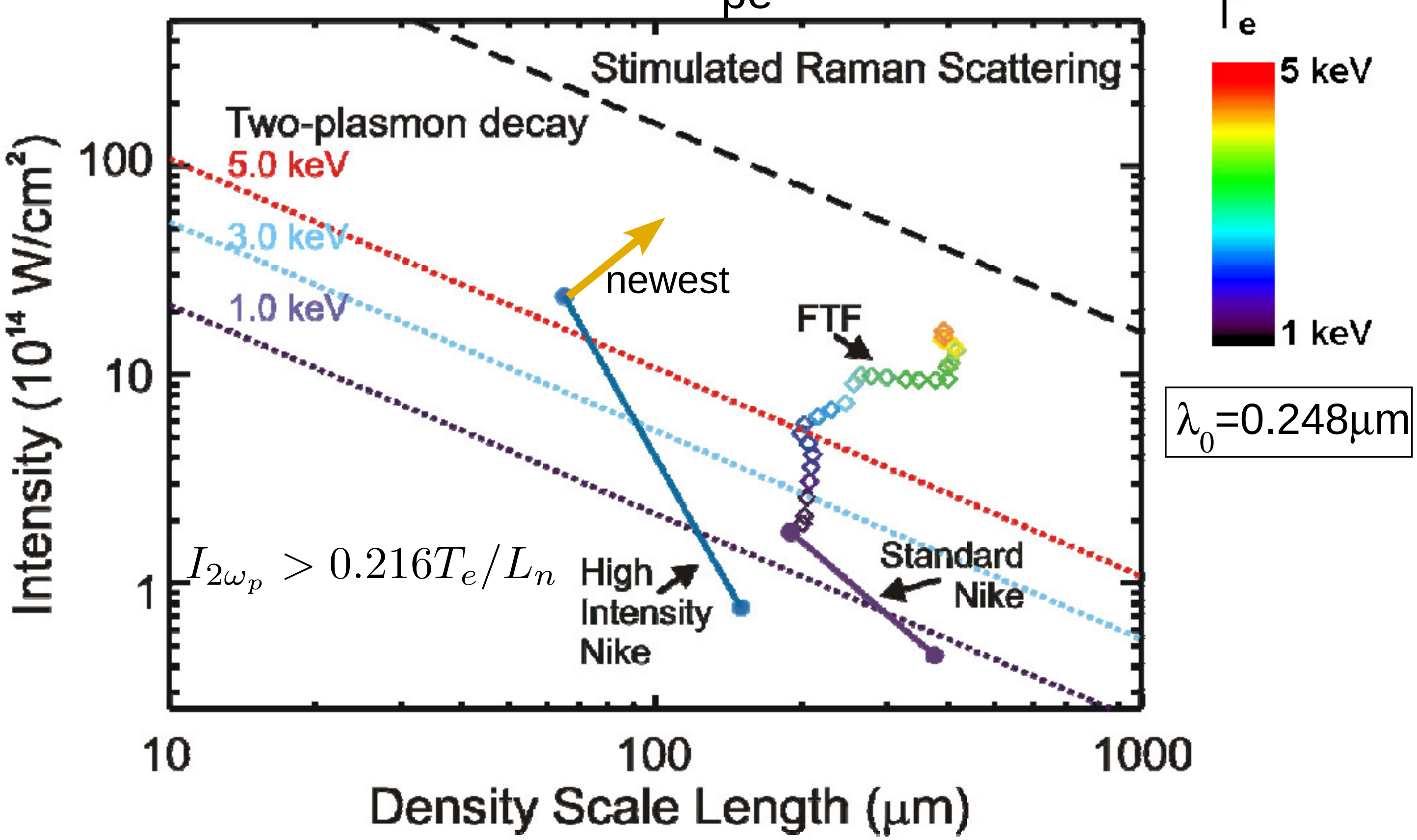
The sensitivity to hot-electrons is similar to results found at UR/LLE[1]



[1] R.P.J. Town et al., LLE Review 79, 121 (1999).

Current status: $2\omega_{pe}$ impact is still uncertain

Nike has been reconfigured to produce spike pulses (~400ps), with some beams focused to ~100μm spots. Experiments so far have shown no evidence of $2\omega_{pe}$.

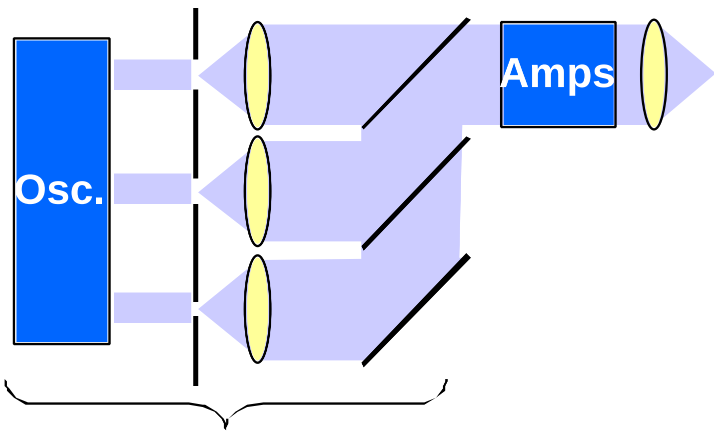


Ongoing efforts are focused on reducing spots to ~50μm, and will shoot pre-heated low-density foams; both should increase I/I_{thresh} another ~10x

(Weaver et al., Phys. Plasmas May 2007)

Zooming the focal spot during the implosion improves the laser-target coupling and symmetry

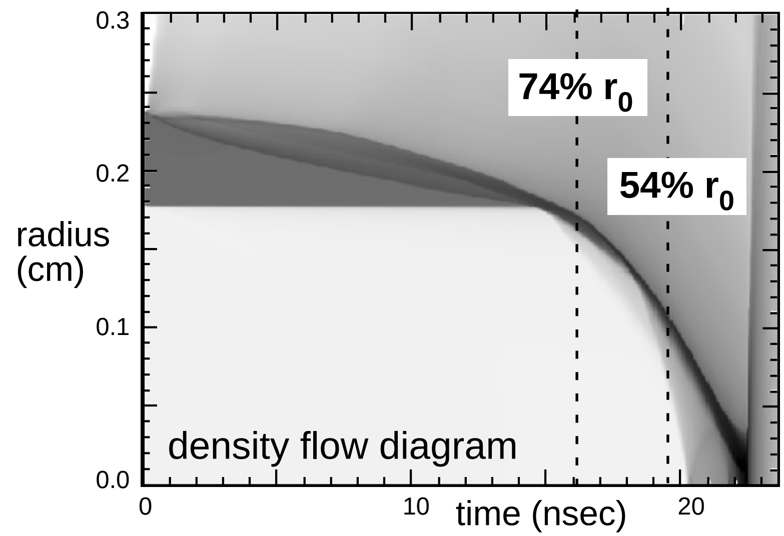
For image-relayed lasers (e.g., KrF), "zooming" is done by switching between differently sized apertures during the pulse. All implementation is at the laser's low-power front end.



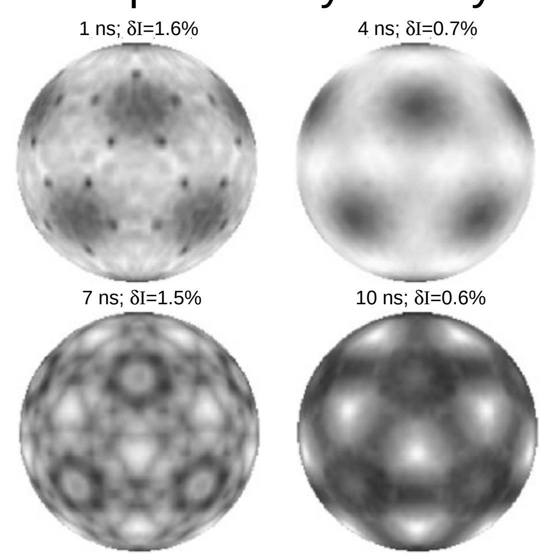
Front end of (very simplified) laser

	With Zoom	Without Zoom
Yield	165 MJ	151 MJ
Laser Energy	1.3 MJ	2.1 MJ
Gain	127	72

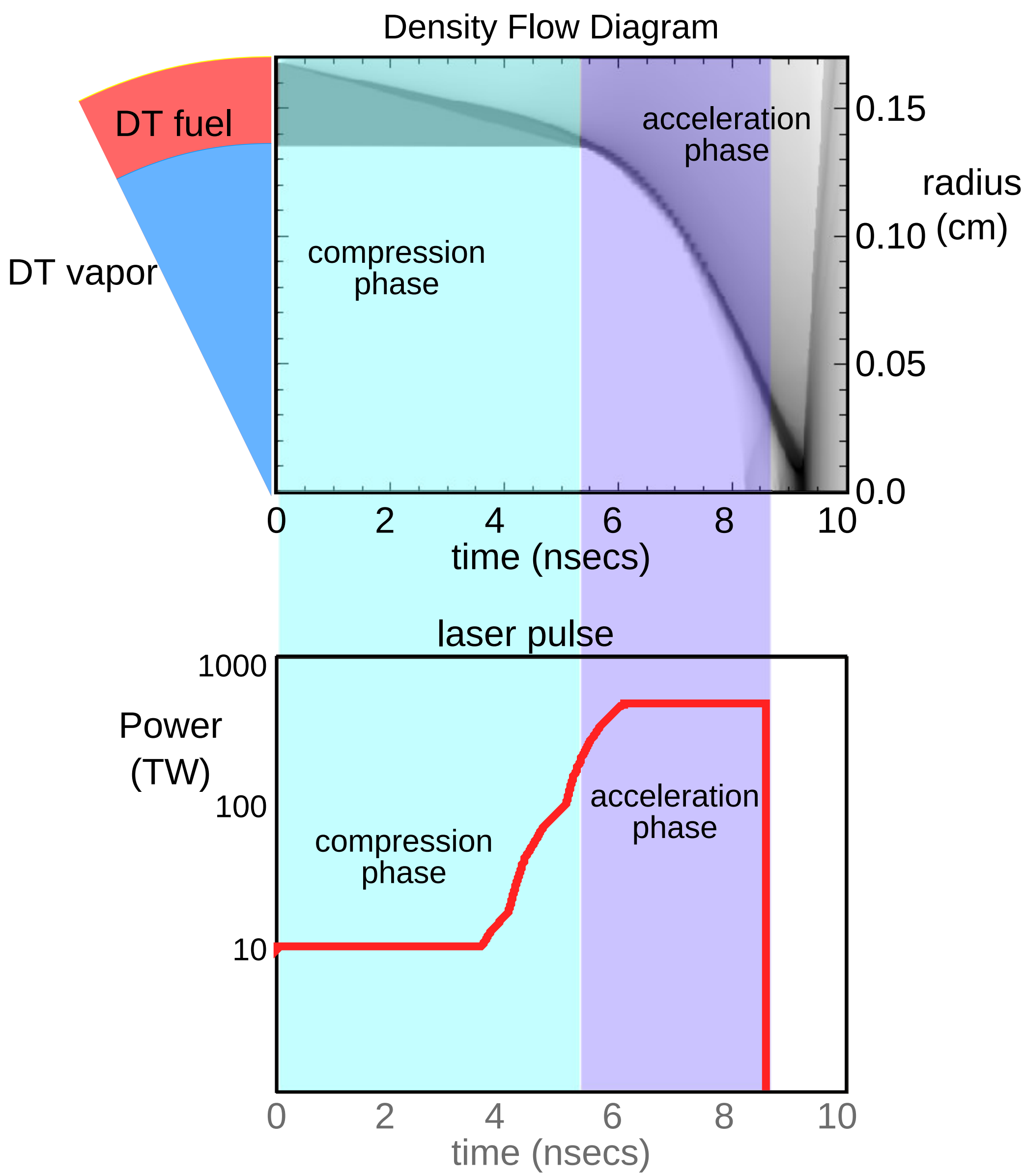
zooming can significantly decrease energy needed



zooming can increase energy deposition symmetry



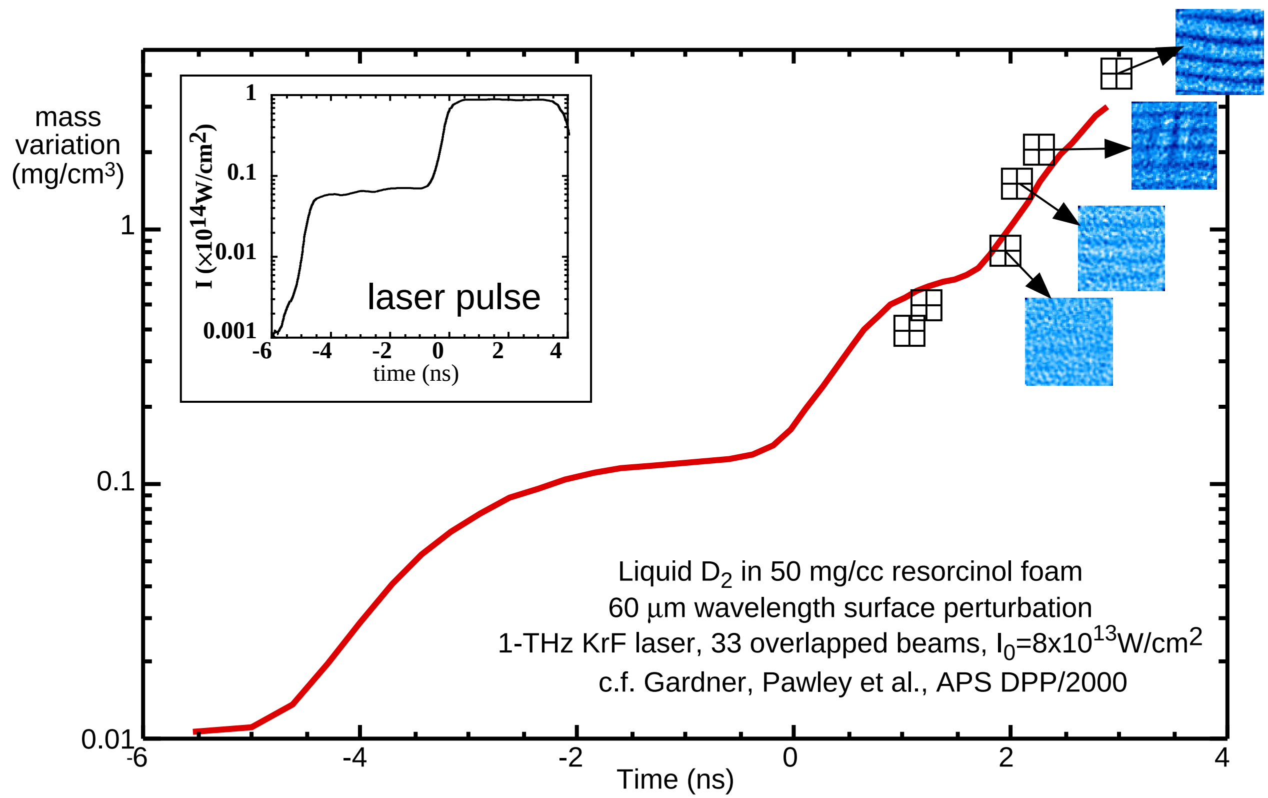
Hydrodynamic stability is still the main issue in direct drive



During compression, there is Richtmyer-Meshkov (RM) growth. Growth (≲10X) is not exponential, but seeds RT.

Rayleigh-Taylor (RT) exponential growth begins with acceleration of shell. Growth can be ~10^2-10^4 or more

RT growth has been checked and simulation code benchmarked on Nike laser



Experimental measurements show that the FAST hydrocode agrees with observation in relevant regimes.

How good is the “simple formula” for Rayleigh-Taylor growth?

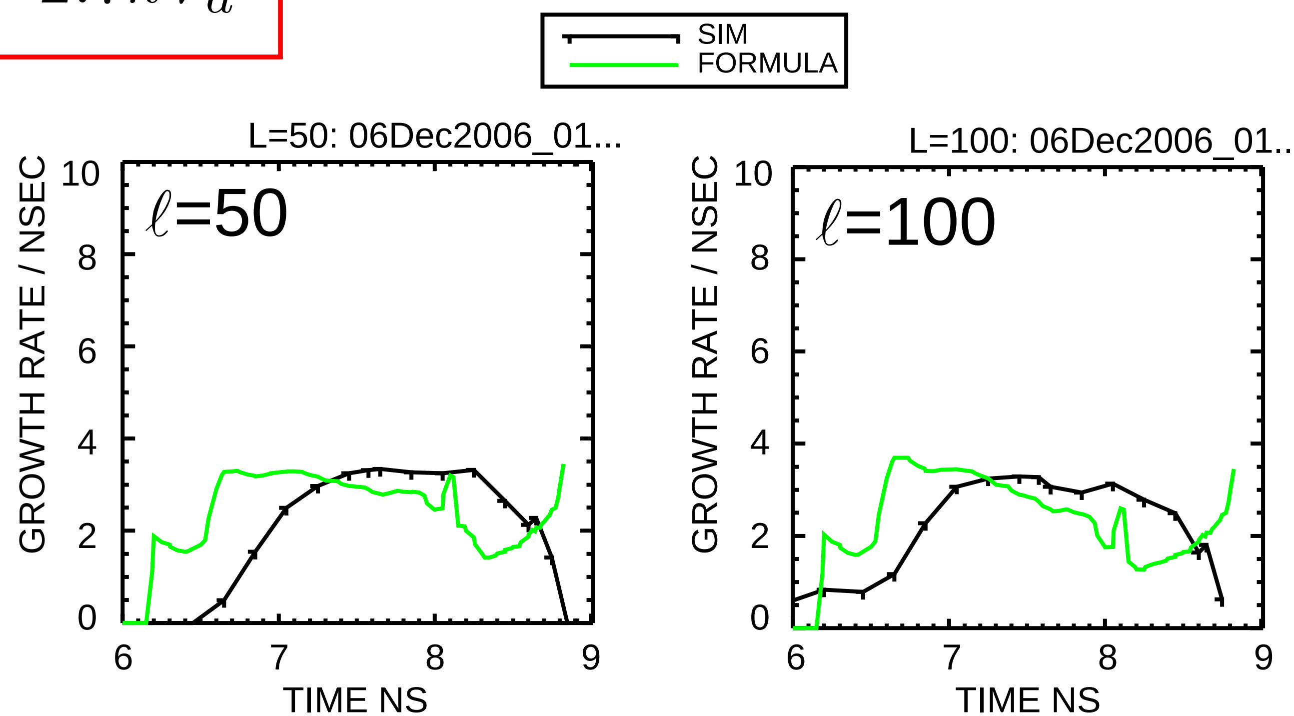
Simulations show rough agreement

simple dispersion relation
(*Betti et al., Phys. Plasmas* **5**, *1446 (1998).*):

$$\gamma = \sqrt{\hat{A}_T kg + \delta^2 k^4 L_0^2 V_a^2 + (\omega^2 - \frac{1}{\xi_l})k^2 V_a^2} - \delta k^2 L_0 V_a - \hat{\beta} k V_a$$

$$\boxed{\gamma_{DT} \simeq 0.94\sqrt{kg} - 2.7kV_a}$$

Single mode and multimode simulations show that RT growth rates are roughly in accordance with the dispersion formula



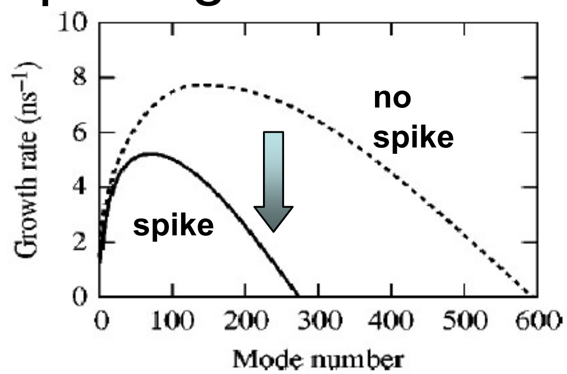
STABILITY

A. Schmitt et al., APS/Div. Plasma Phys. Conf. 2006

Recent work has suggested ways of producing additional suppression of RM & RT

Spike prepulse can help mitigate both RM & RT perturbation growth

Strong reduction of growth rates due to increased ablation velocity, particularly for high modes.



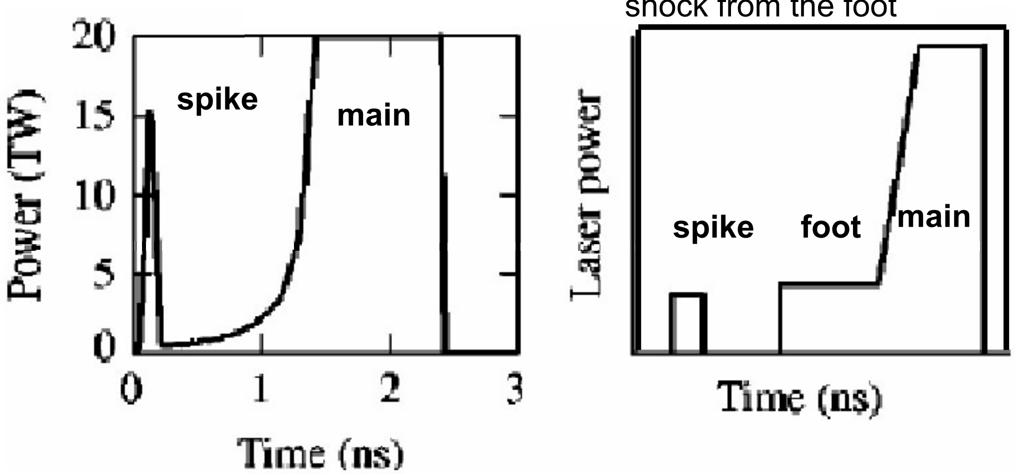
Goncharov et al. PoP ***10****, 1906 (2003).*

Decaying shock (DS)

Strong spike, target adiabat is shaped by the decaying shock from the spike

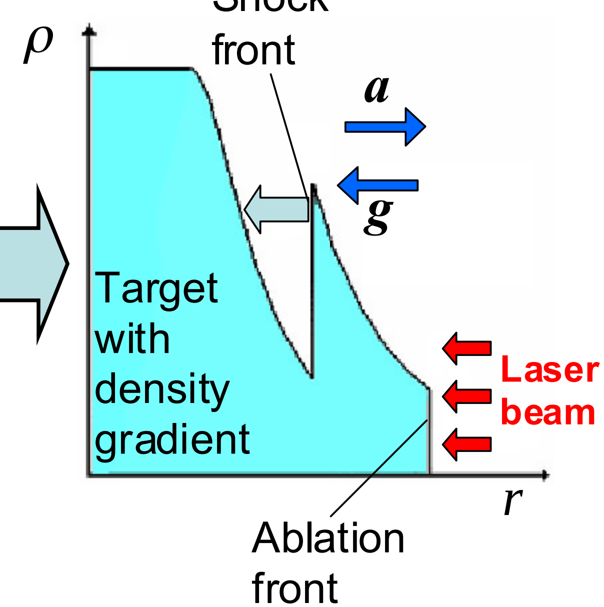
Relaxation (RX)

Weak spike shapes a graded density profile, target adiabat is shaped by the decelerating shock from the foot



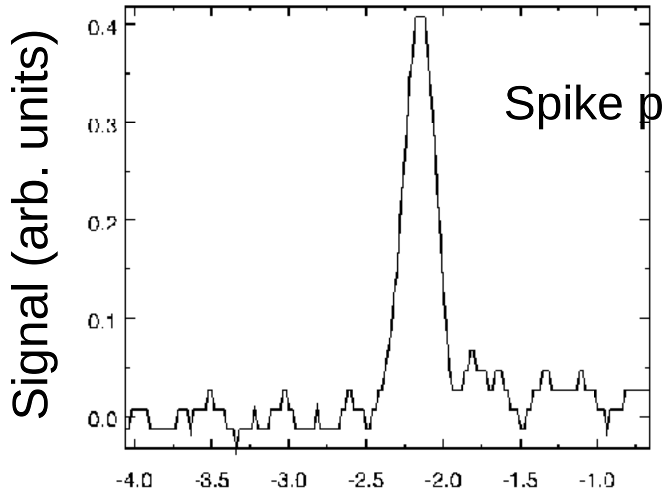
J. P. Knauer et al., PoP ***12****, 056306 (2005).*
Theory: K. Anderson and R. Betti, PoP ***10****, 4448 (2003); R. Betti et al., PoP* ***12****, 042703 (2005).*

Relaxation spike used for present Nike experiments



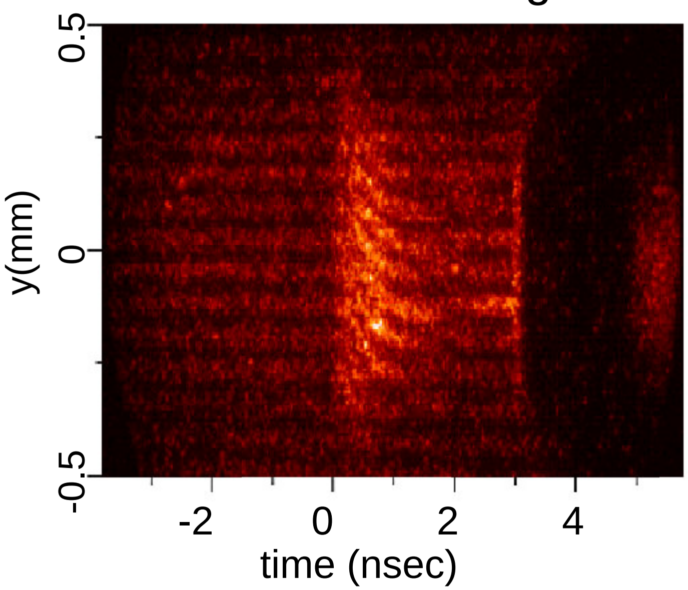
N. Metzler et al., PoP ***6****, 3283 (1999).*

Spike prepulse physics tested with new capability installed on Nike

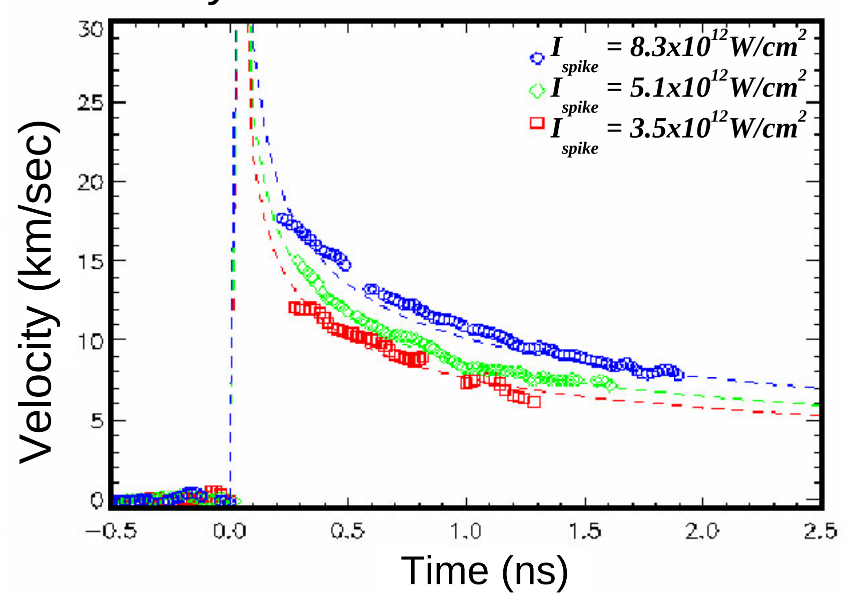


Spike pulse in Nike front end

VISAR Streak Image



Theory matches Observation

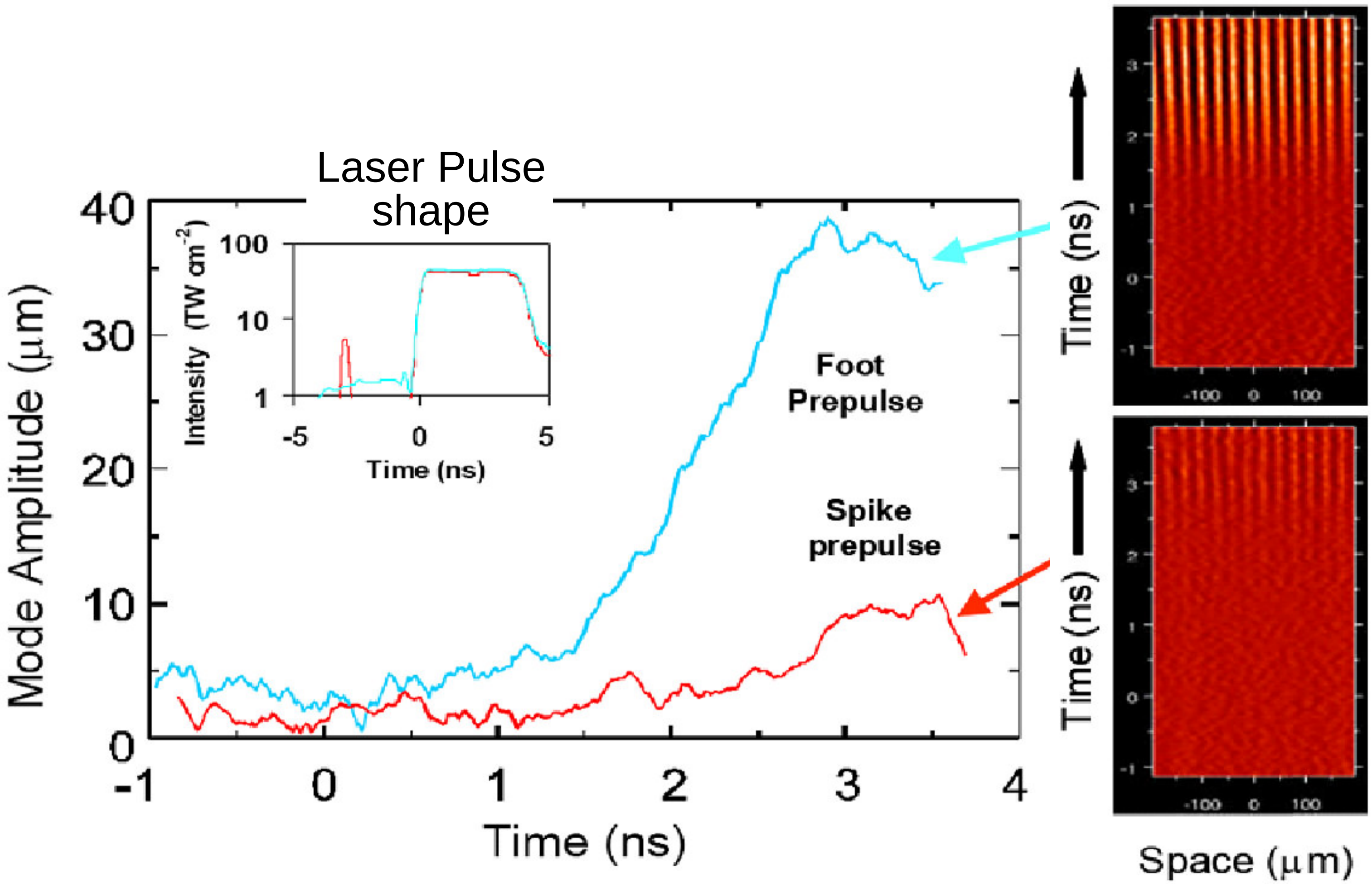


STABILITY

J. Oh experiment in J. Weaver, et al., APS/Div. Plasma Phys. Conf. 2005

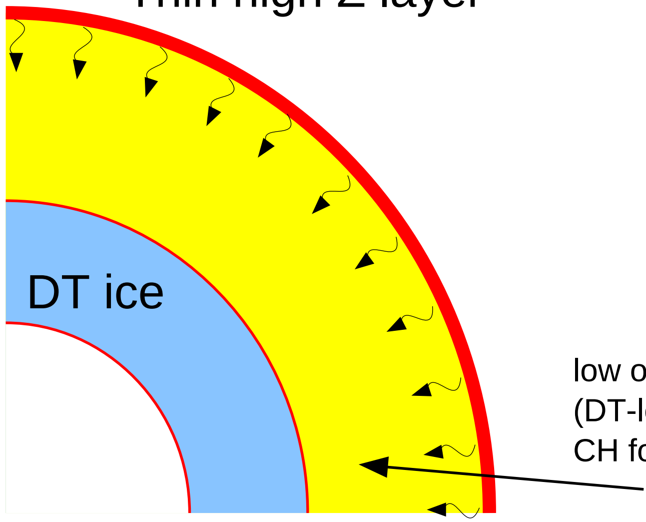
Low-amplitude spike prepulse suppresses ablative RM growth triggered by target surface roughness

NRL



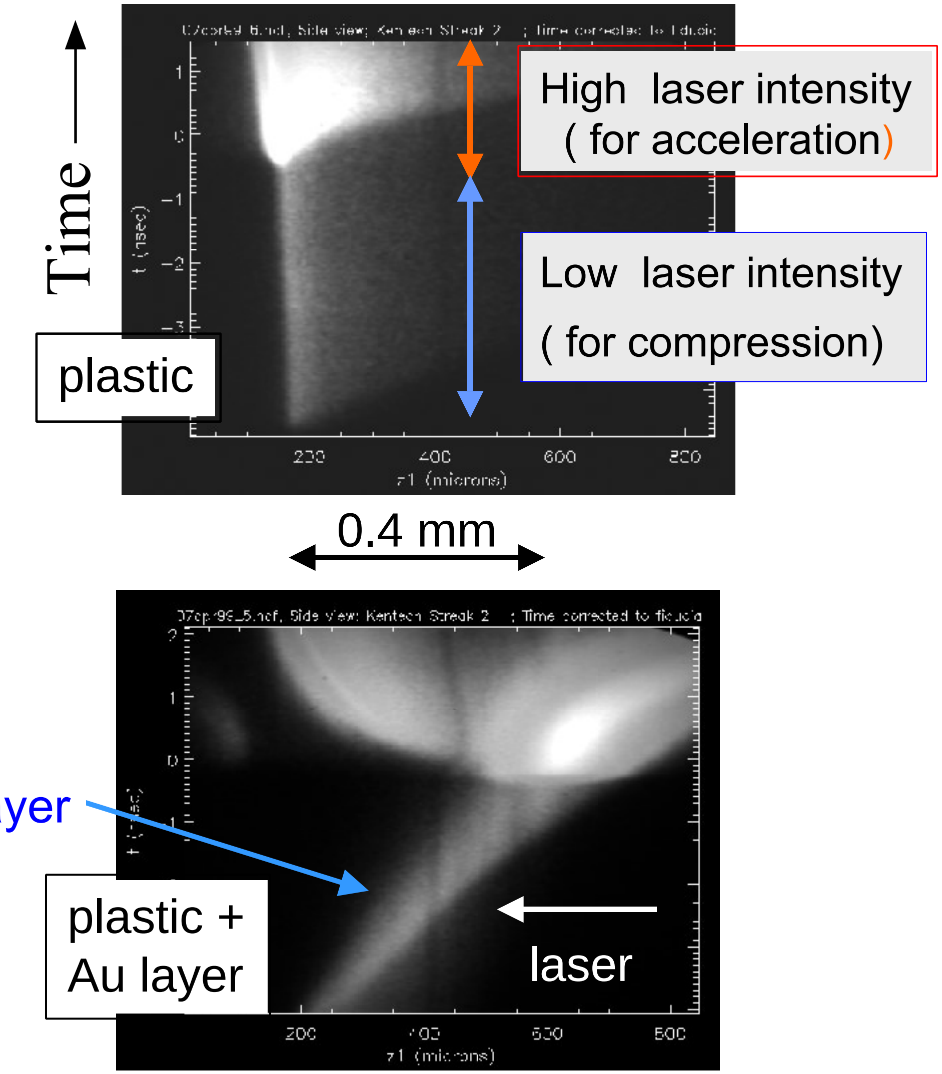
J. Weaver et al., APS/Div. Plasma Phys. Conf. 2006

A thin high-Z layer can also be used to reduce initial perturbation growth



X-rays from high-z layer enhance energy transport into the target, and produce a large plasma that can buffer and reduce the small scale laser nonuniformity

Effect of Au layer on plasma



Side-on views of x-ray emission

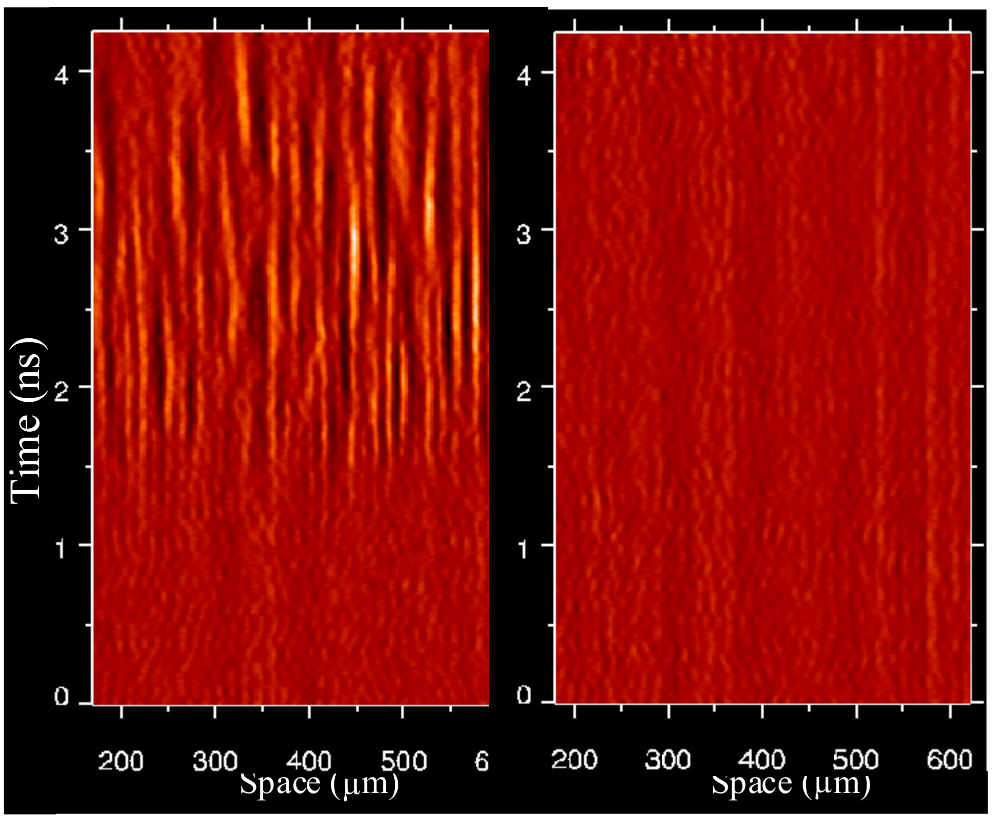
S. Obenschain et al., Physics of Plasmas **9**, *2234 (2002).*

Experiments clearly show that the addition of a thin high-Z layer reduces the effects of laser nonuniformity substantially

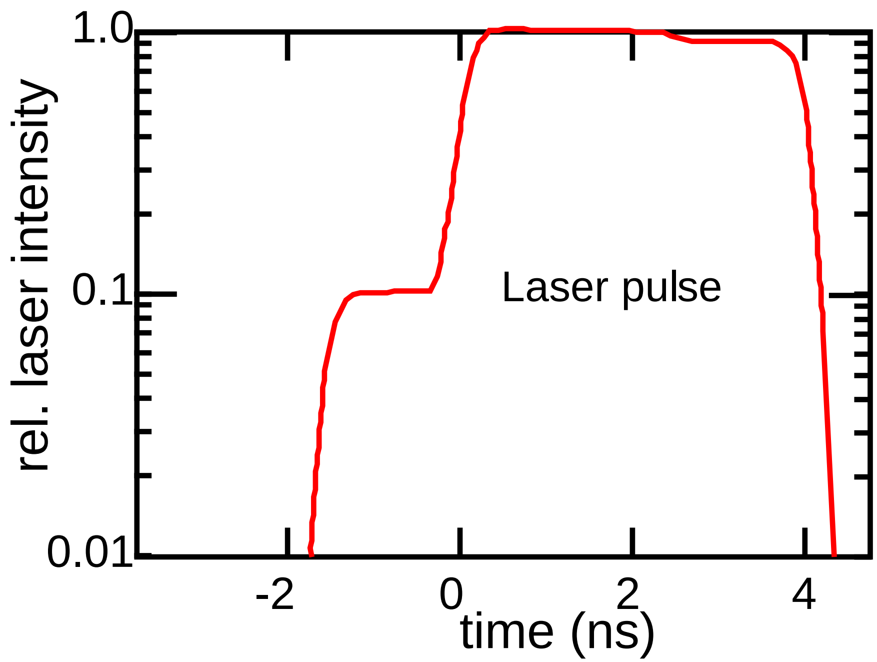
Laser imprint suppression with high-Z layers is working at higher foot intensities (8 TW/cm^2 - within a factor of 2 of the pellet designs)

Flat CH: strong imprint growth

Flat CH + 450Å Au: imprint is suppressed

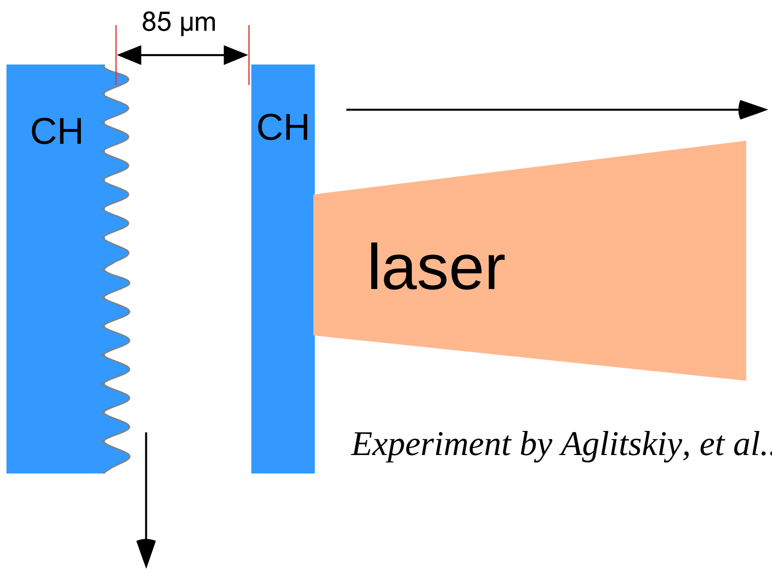


streak camera results of face-on x-ray backlight targets shot on Nike KrF laser



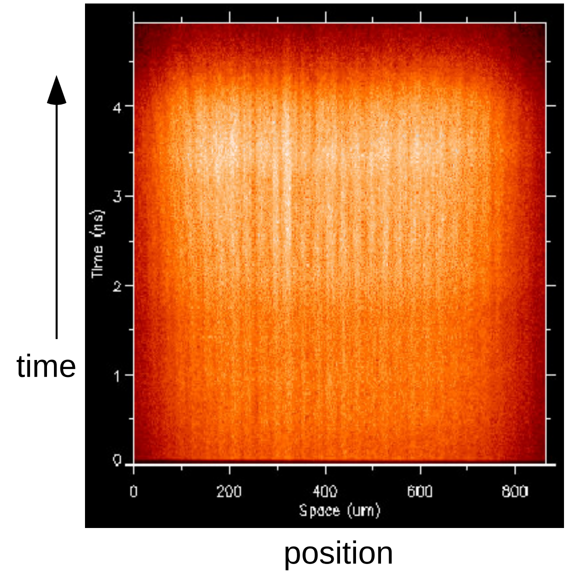
M. Karasik et al., APS/Div. Plasma Phys. Conf. 2006

Double-foil collision experiment examines physics of stagnation instabilities

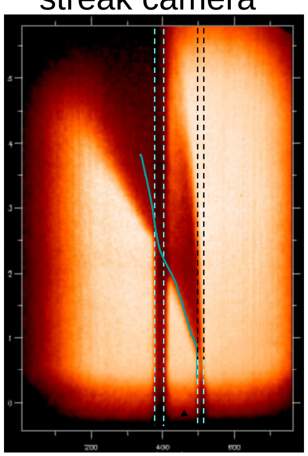


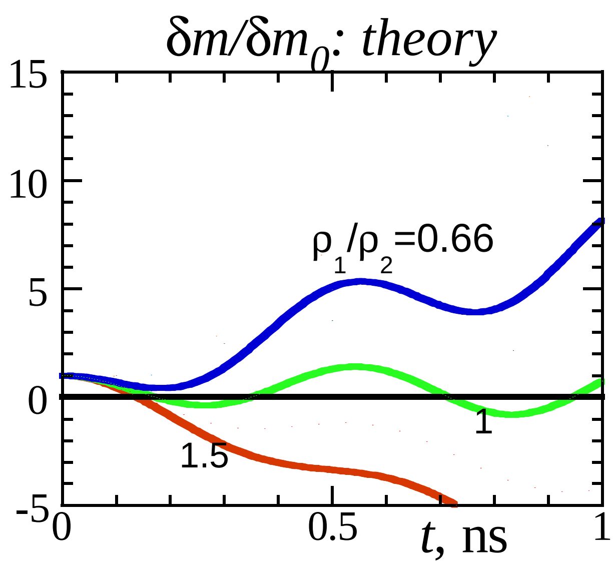
Experiment by Aglitskiy, et al....

Face-on radiography
streak camera



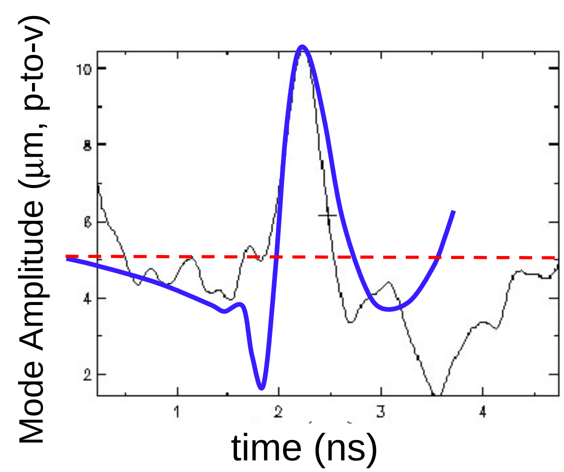
side-on radiography
streak camera





(A. Velikovich, NRL)

Experiment & Simulation



(N. Metzler, SAIC@NRL w/FAST code)

Y. Aglitskiy, A. Velikovich et al., APS/Div. Plasma Phys. Conf. 2006

Nike program has extensive simulation program

The Nike simulation program has been extensively tested via comparison to experiment in RM, RT, and other hydrodynamic and radiation physics.

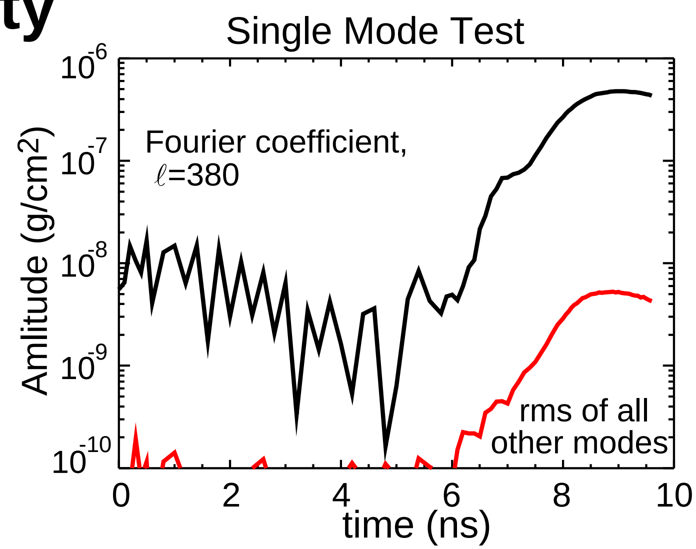
However, calculation and design of large (mid- to high-gain) ICF targets increases the challenges for the simulation code. Codes are asked to accurately describe perturbation growth from miniscule to large levels ($>10^5$), and over a broad range of wavelengths ($1<\ell<\sim500$). These design constraints are formidable, and resulted in upgrades to the FAST code.

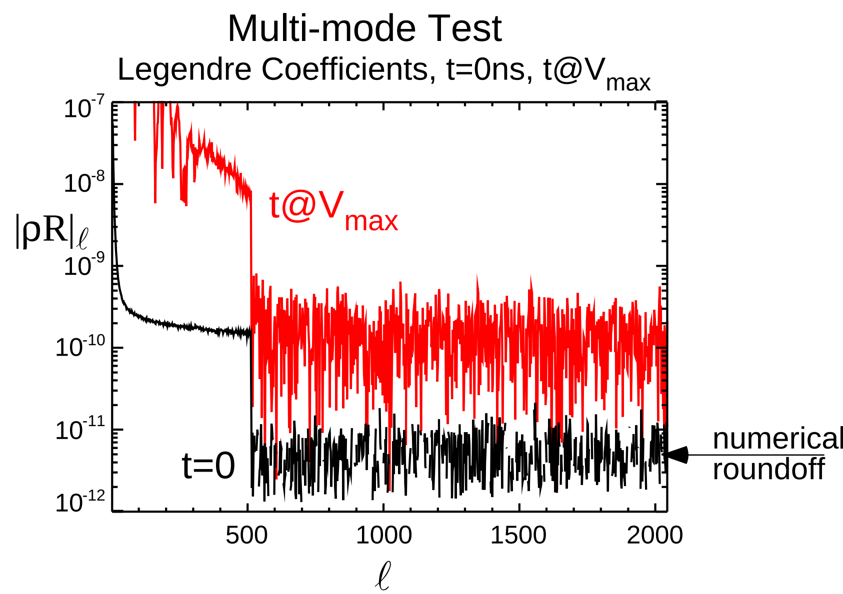
FAST radiation hydrocode:
- 1-3D, planar, cylindrical or spherical on orthogonal grids
- LTE/nonLTE STA multi-group radiation diffusion
- flux-limited electron and ion thermal conductivity
- TNburn with alpha particle diffusion
- laser raytracing and absorption
- FCT and/or low-noise hydro algorithms

The low-noise capabilities of the FAST code were created to solve the linear (small-amplitude perturbation) problem

Consistency check I: Mode fidelity

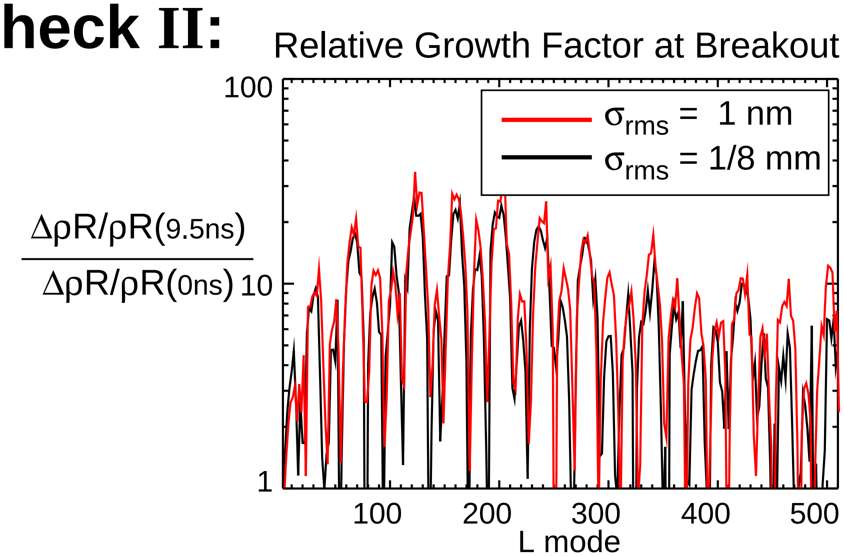
Single mode and multimode tests show great mode fidelity





Consistency check II: Linearity

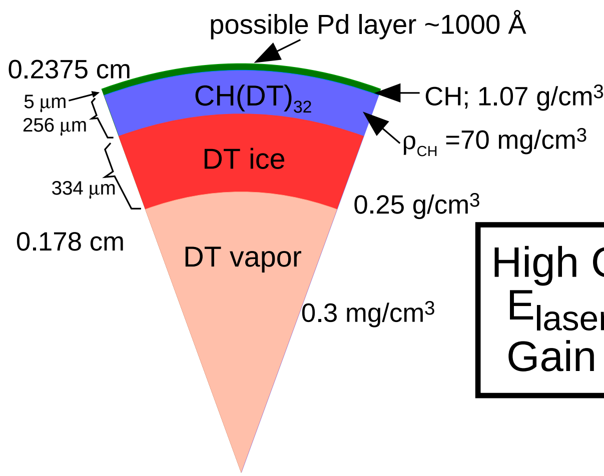
Relative Growth Factor at Shock Breakout: relaxation shock RX10 pulse



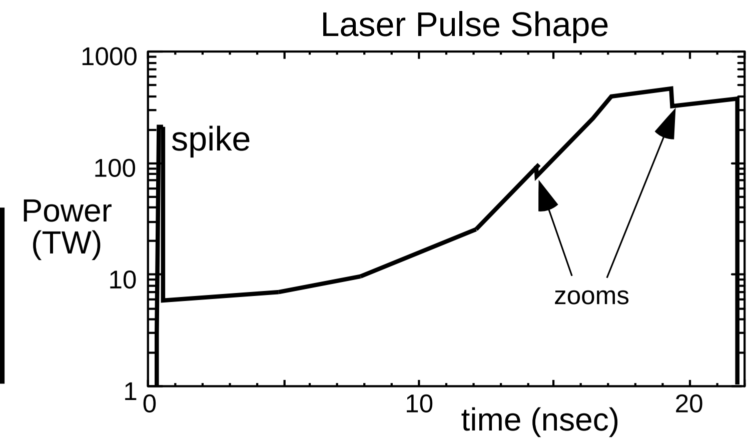
SIMULATION

A. Schmitt, S. Zalesak et al., APS/Div. Plasma Phys. Conf. 2006

High gain target uses KrF laser with zooming and "spike" prepulse and gets gain >150 in 2D

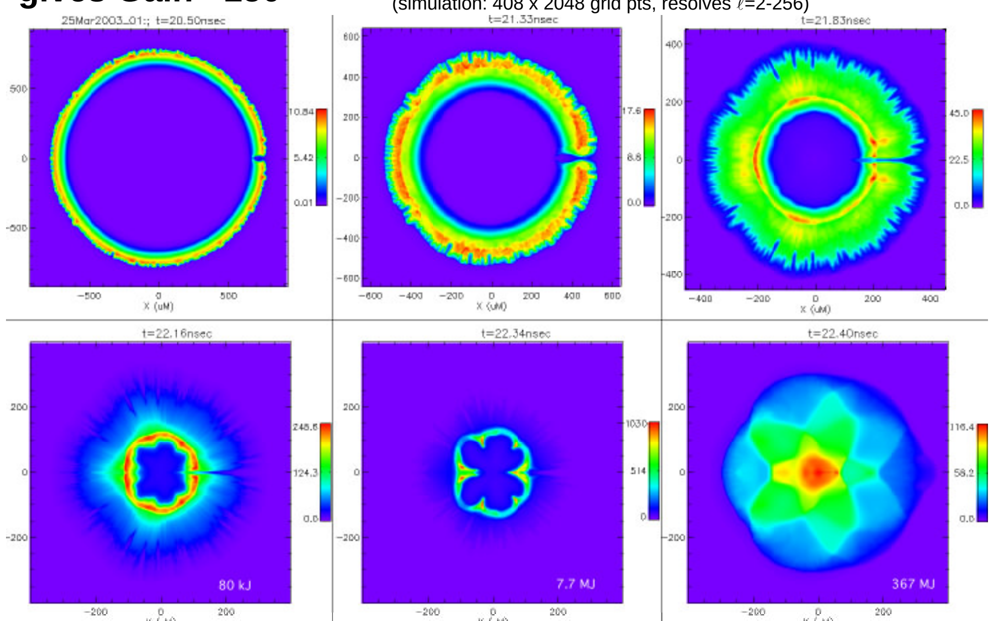


High Gain KrF target
E_{laser} 2.6 MJ
Gain 150-170



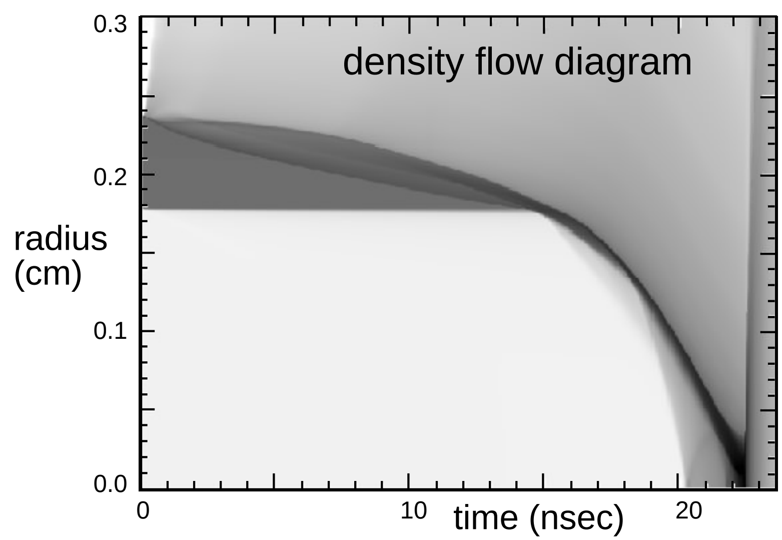
High Gain KrF pellet with stabilizing “spike”:
0.125μm rms outside, 1μm rms inside surface & 1 THz optical smoothing:
gives Gain >150

(simulation: 408 x 2048 grid pts, resolves ℓ=2-256)



SIMULATION

images of density at six different times during the implosion



Schmitt et al., Phys Plasmas ***8,*** *2287 (2001).*

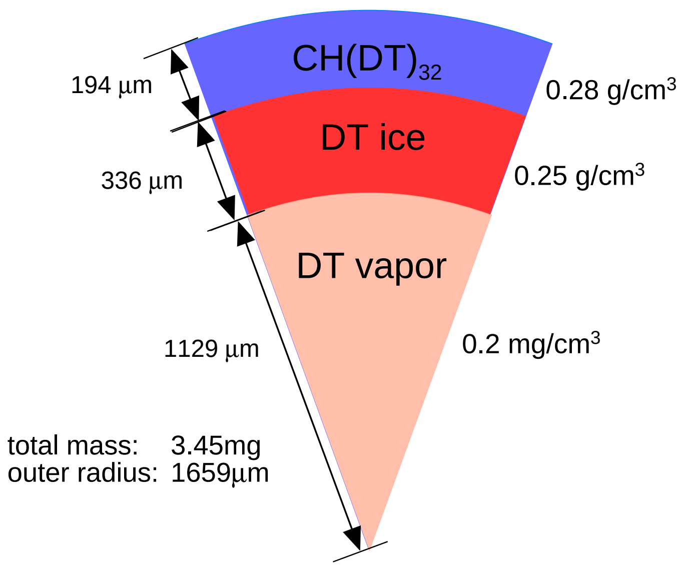
We have designed a target with different 1.2MJ laser pulse shapes

Parameters for the 1.2 MJ pellet, with different pulses

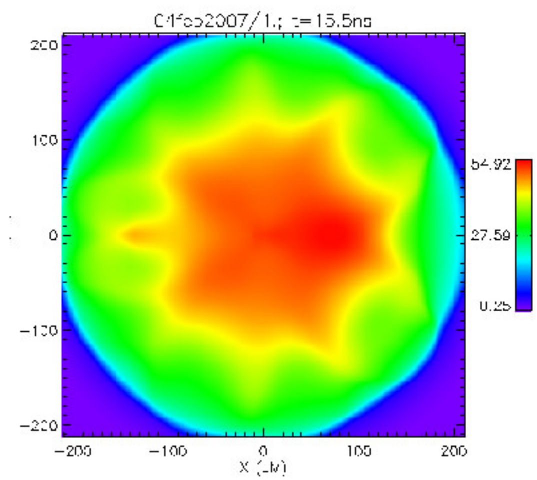
Pulse	Gain:1d	2d	Max. e-folds	IFAR(1)	<α>(2)	ρR	Margin(3)
C1	140		6.7	43	2.8	2.0	0.42
C2	112		5.4	38	3.7	1.8	0.46
RX1	154	88	5.4	40	2.5	2.4	0.44
RX2	88	55	3.1	24	6.2	1.6	0.61

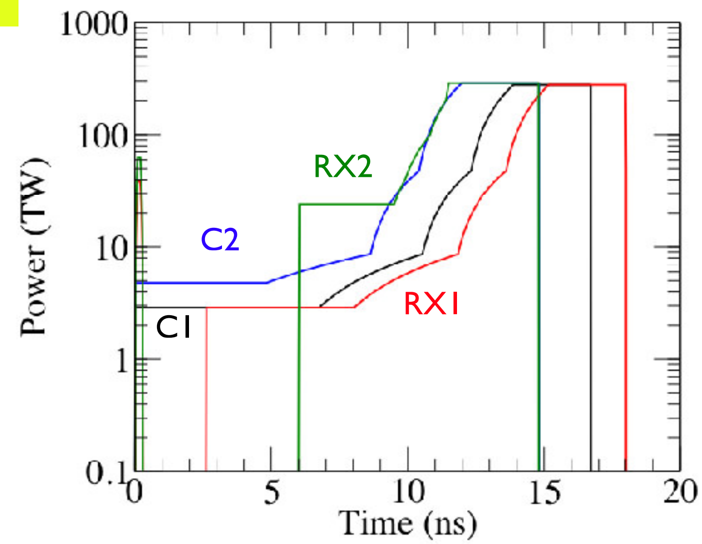
(1) In-flight aspect ratio, measured at 2/3 R
(2) Mass averaged about 1/3 peak density at max. velocity
(3) Fraction of peak kinetic energy remaining at gain=1

2d ℓ=2-256 with "NIF-spec" outer+inner finish+ISI@1THz



total mass: 3.45mg
outer radius: 1659μm





SIMULATION

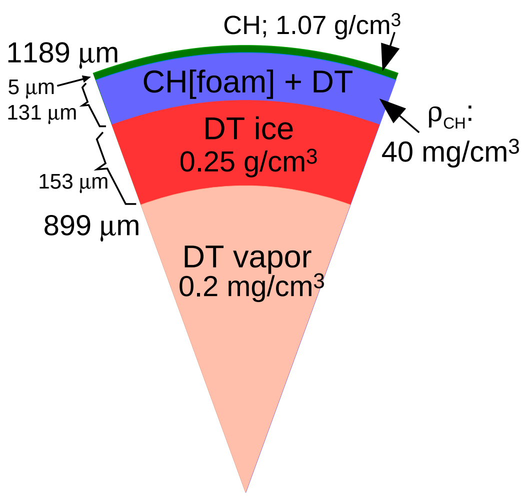
Jason Bates et al., APS/Div. Plasma Phys. Conf. 2006

The Current Focus is on ~500 kJ targets for FTF

NRL

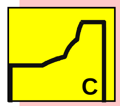
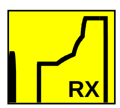
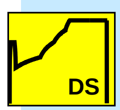
A wide variety of targets designs have been produced based on a single pellet driven by different pulse shapes with I_{max} ~2-2.5 x 10^{15}W/cm^2

pellets are low-aspect ratio (AR_0~3.1), designed for high pressure drive



480 kJ target

Parameters for the 500 kJ pellet, with different pulses

	Pulse	Gain 1d	Gain 2d (hi-res)	Foot[5] (%)	<α>[3]	Max. e-folds[1]	IFAR[2]	ρR	Margin[4]
	C0.5	99	0	0.5	2.3	8.8	49	1.88	0.44
	C1.75	66	47	1.75	4.5	5.6	33	1.50	0.44
	C3.0	42	--	3.0	6.2	4.4	24	1.34	0.43
	C4.0	20	--	4.0	7.3	3.7	21	1.18	0.31
	RX0.5	101	--	0.5	2.1	8.1	46	2.08	0.49
	RX1.75	79	0.7	1.75	3.0	6.2	36	1.63	0.38
	RX2.5	75	66	2.5	3.4	5.4	30	1.64	0.44
	RX5.0	63	55	5.0	4.6	4.5	26	1.55	0.43
	RX7.5	49	3.4	7.5	5.9	3.8	22	1.39	0.34
	RX10	16	0.8	10.0	6.8	3.4	19	1.18	0.21
	DS0.8	69	62	0.8*	3.5	5.7	36	1.47	0.33
	DS2.2	49	6.5	2.2*	5.6	3.7	22	1.38	0.36

(1) From 1-D RT dispersion relation $0.9\sqrt{kat} - 3kV_{ablation}$
(2) In-flight aspect ratio, measured at 2/3 R_0.
(3) Mass averaged from peak density to 1/e peak density, at peak velocity.
(4) Fraction of peak kinetic energy remaining when gain=1.
*(5) Foot power/Main pulse power; *for DS pulses: Spike energy/Total Energy.*

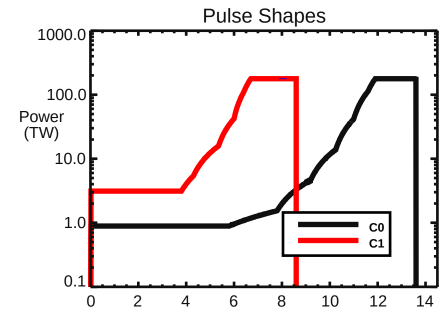
SIMULATION

A. Schmitt et al., APS/Div. Plasma Phys. Conf. 2006

High-spatial frequency mode growth can be stabilized in FTF targets

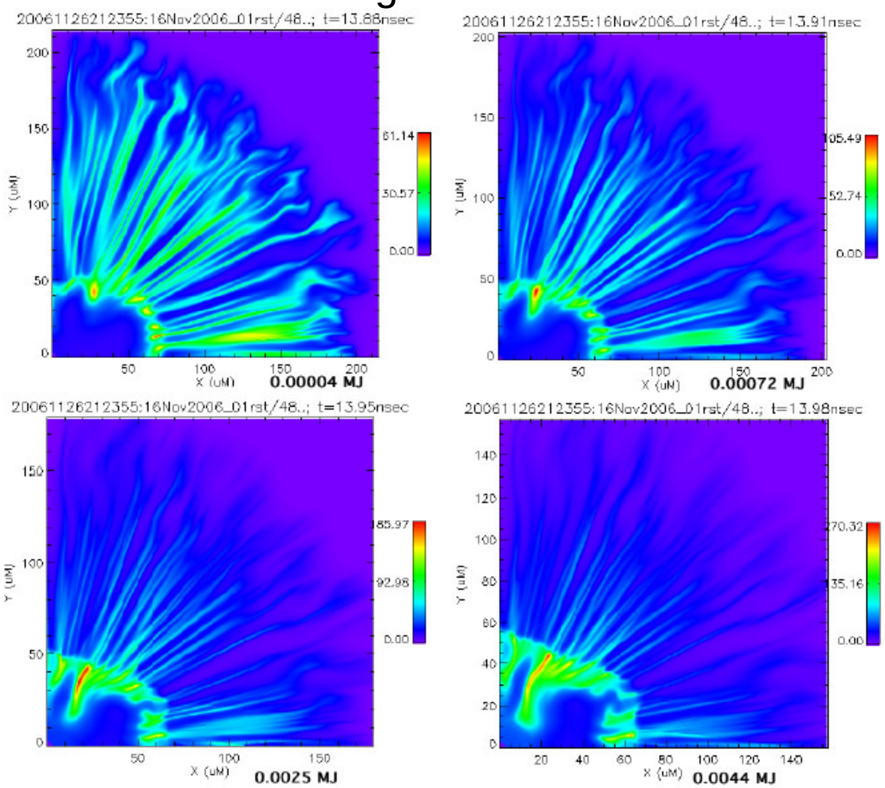
The higher foot/higher adiabat pulses stabilize the high-spatial-frequency instability growth so that primarily low modes are important

pellets have initial “NIF-spec” outer surface finish;
modes L=2-512 are resolved (660x2048 grid)

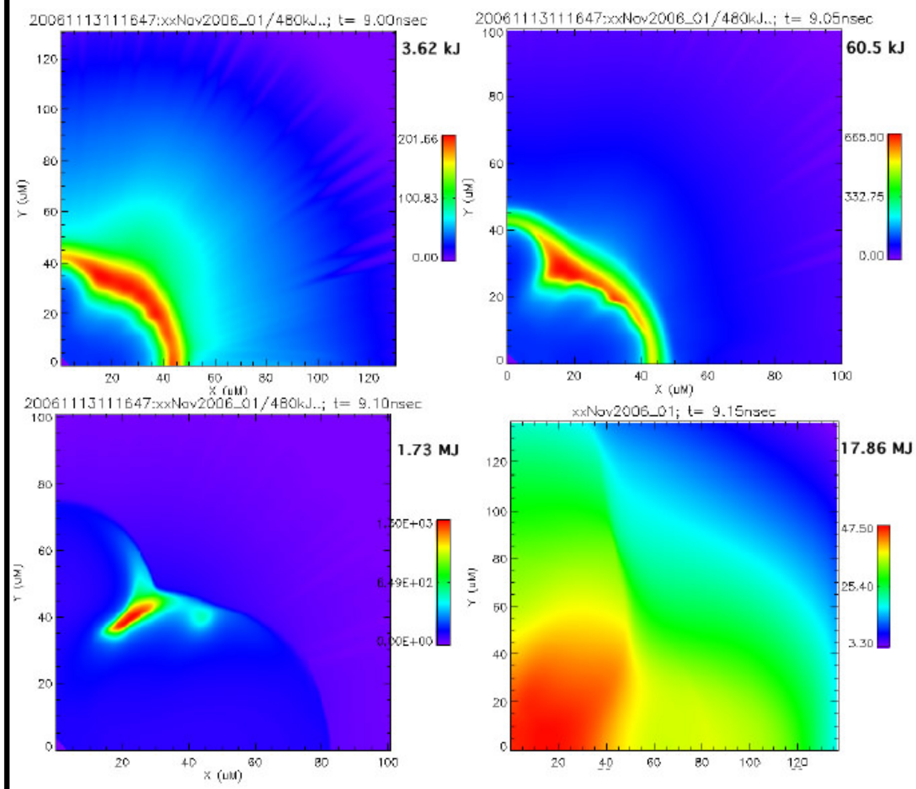


“C0.5" pulse
Y = 4 kJ

density images near stagnation and burn



“C1.75" pulse
Y = 18 MJ



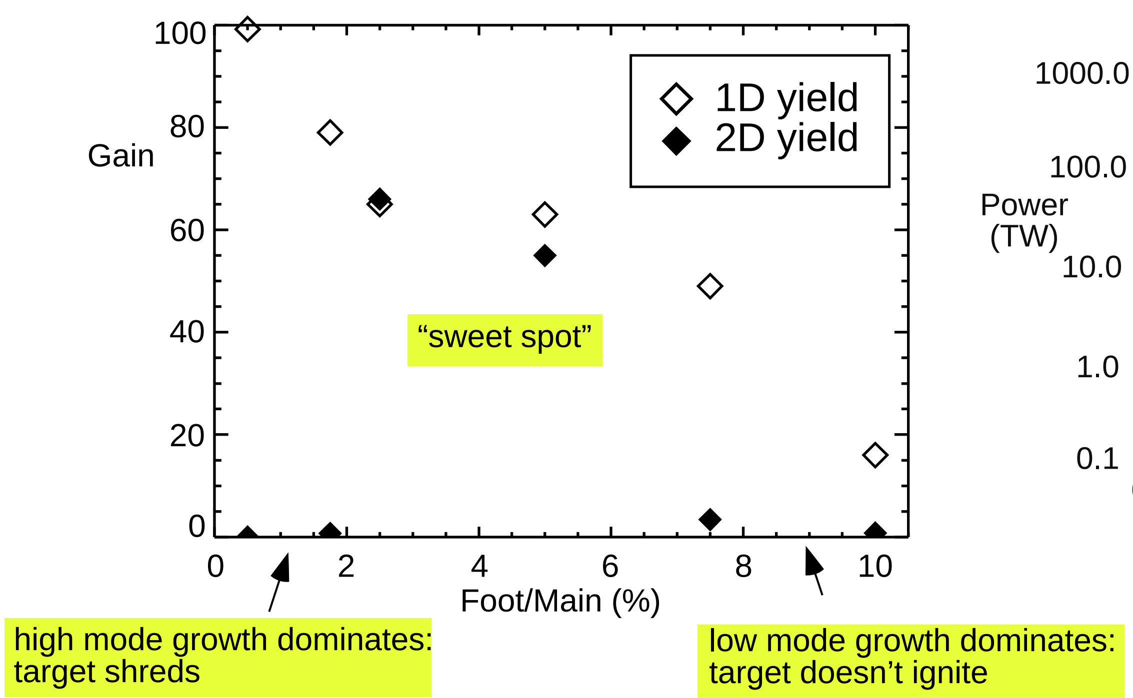
SIMULATION

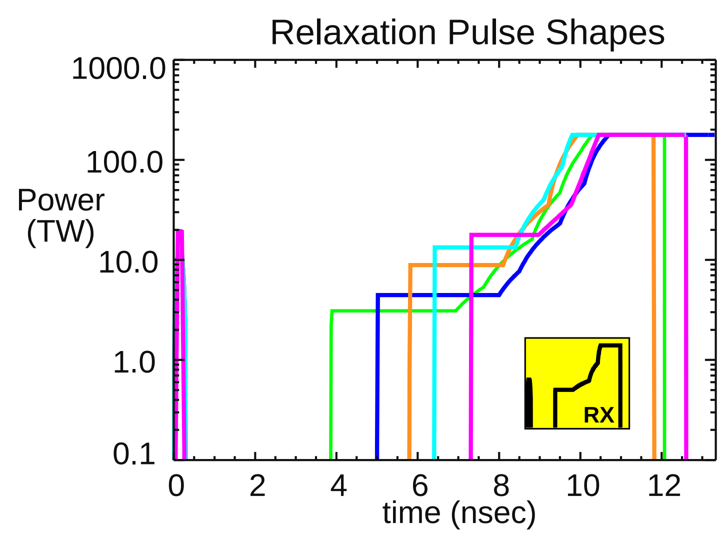
A. Schmitt et al., APS/Div. Plasma Phys. Conf. 2006

Finding the optimum gain in 2D: RX pulses perform well

Increasing the foot pulse amplitude increases the adiabat
- decreases the gain (1D)
- reduces RT at high mode (2D)
- increases sensitivity to low-mode asymmetry (2D)

Relaxation pulse (RX) family of FTF designs





SIMULATION

A. Schmitt et al., APS/Div. Plasma Phys. Conf. 2006

Summary

Laser IFE has come far since its inception due to technical advances and increased understanding of the physics. Experiments have tested key concepts which have been used to design medium-high gain targets.

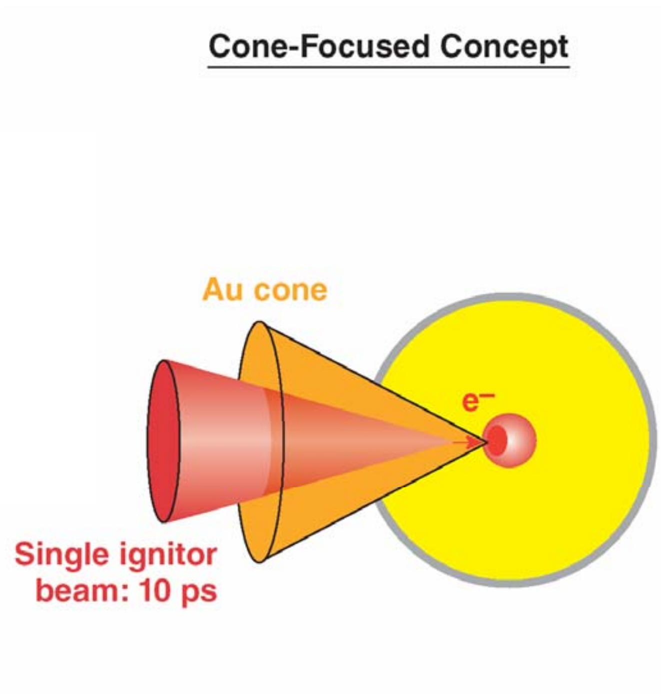
Many problems have been solved or mitigated, but there are still questions:

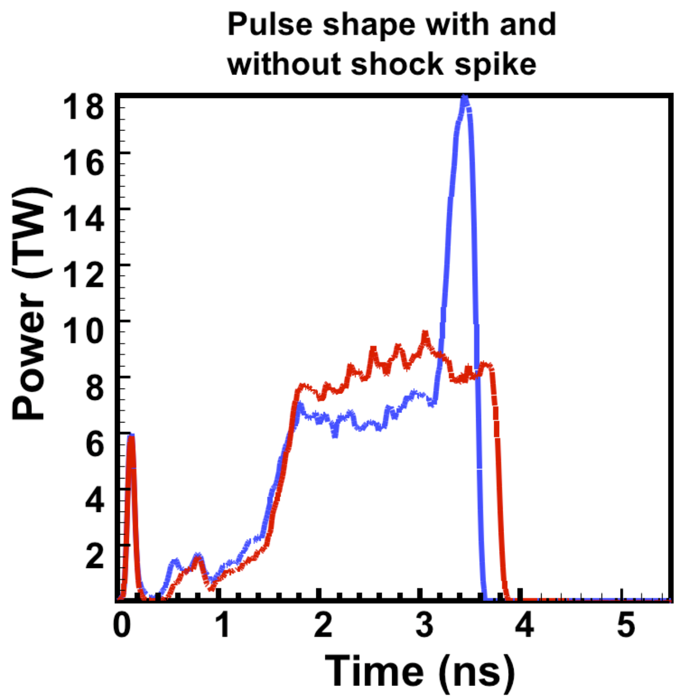
Coupling: improved with shorter λ lasers, optical smoothing, zooming.
Q: what are the intensity (pressure) limits?

Stability: shorter λ lasers, optical smoothing, new ideas (spike, hi-Z layers) have alleviated problem.
Q: How much adiabat shaping is needed?
What is achievable gain?

Simulation/modelling: massively parallel computing has enabled routine use of 2D simulations of entire target; results are promising.
Q: How robust are these ideas, particularly in 3D?
How sensitive are the physics modelling approximations?

FAST IGNITION AND SHOCK IGNITION

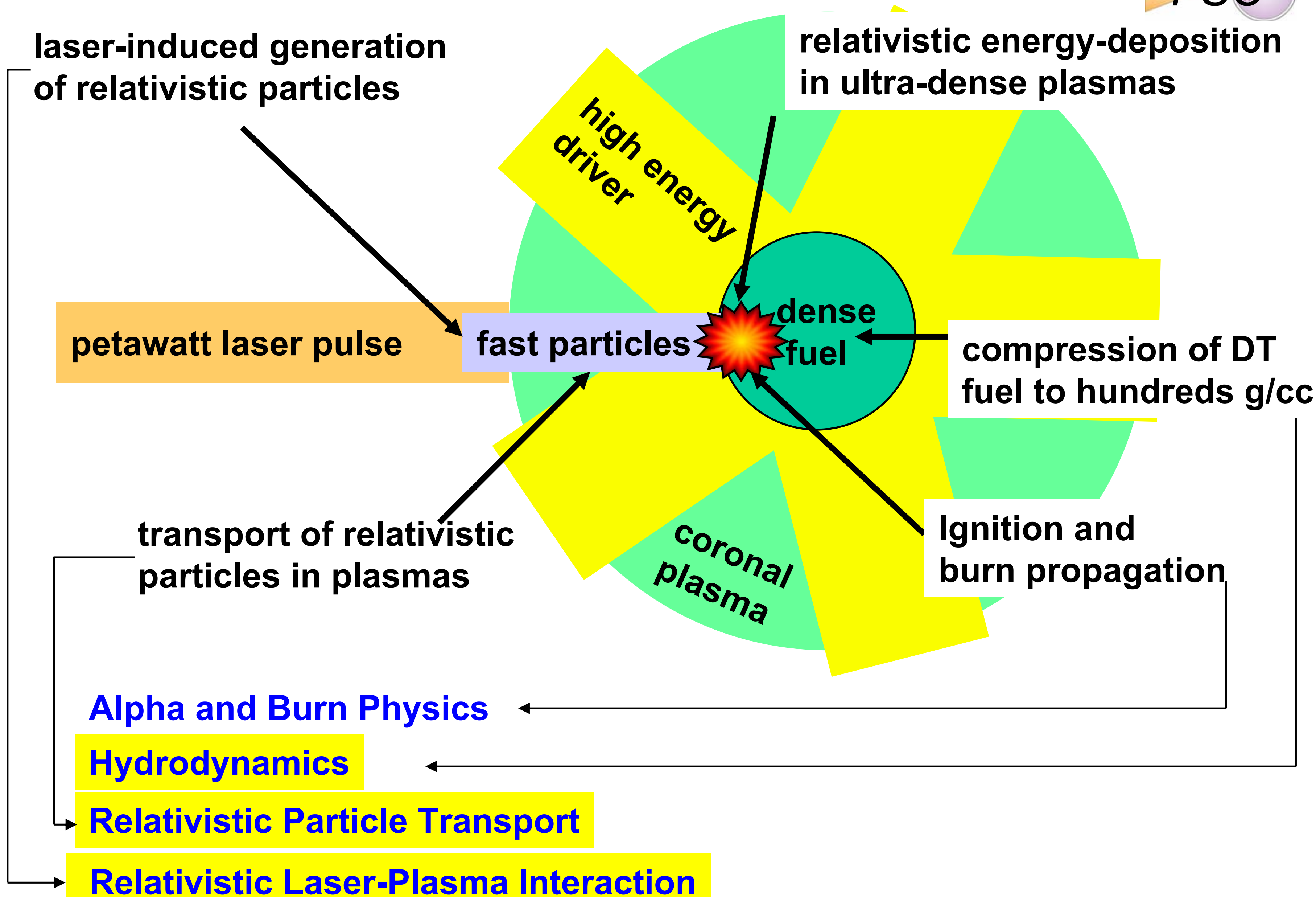




R. Betti
Fusion Science Center and Laboratory for Laser Energetics
University of Rochester

IFE Workshop, San Ramon CA, April 24-27, 2007

Challenges in FI: hydrodynamics and particle transport



Hydrodynamics of Fast Ignition: Fuel assembly and gain curves

Hydro-theory of fuel assembly shows that low velocity, low adiabat implosions are optimal for fast ignition.

$$\rho R \sim E_L^{0.33} / \alpha^{0.55}$$

$$\text{Gain} \sim \frac{1}{V_i^{1.2}} \frac{\rho R}{7 + \rho R}$$

$$\rho \sim V_i / \alpha$$

Fast ignition implosion for given laser energy E_L:

- **Low velocity V_i**
- **Low adiabat α**
- **Large mass**

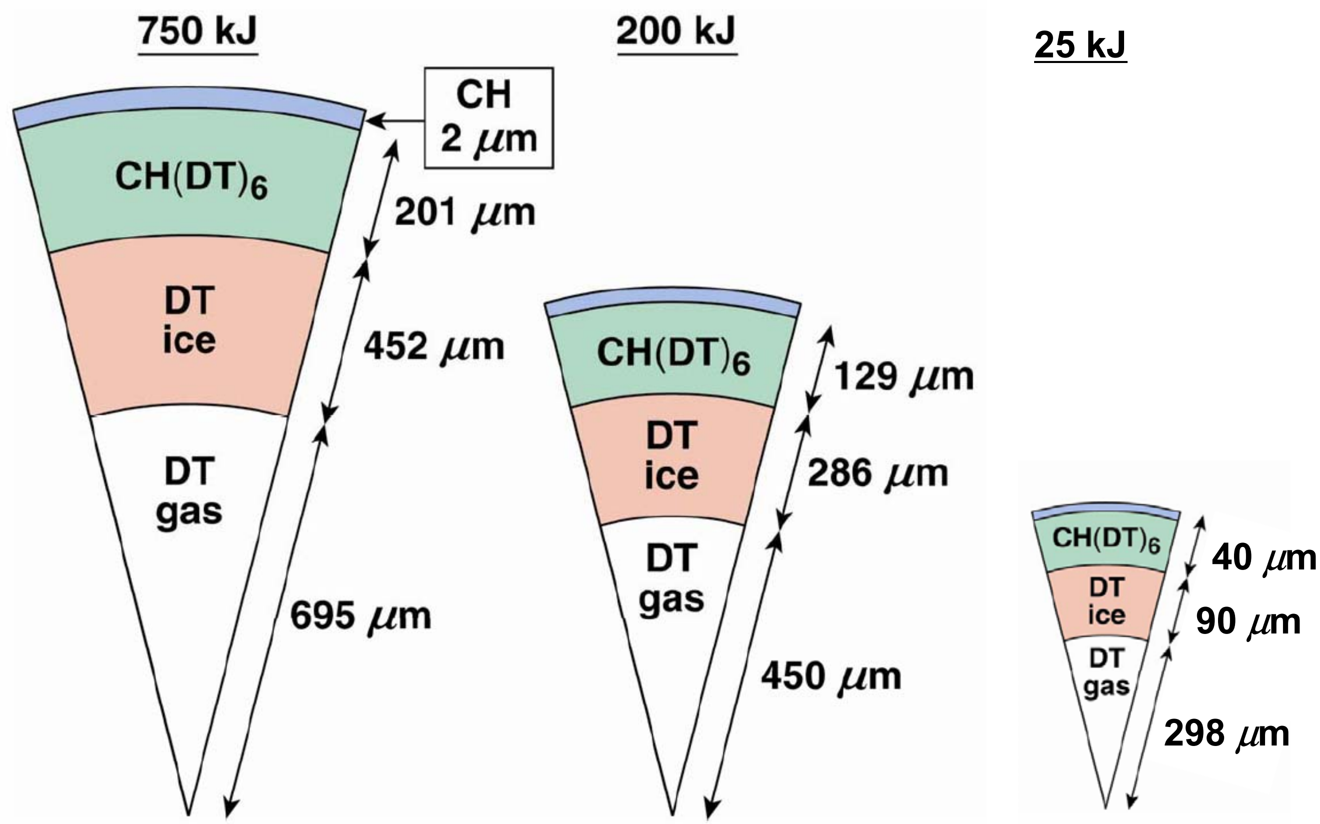
$$< \rho > \approx 300 - 500 g / cc$$

$$\rho \sim uniform$$

Optimum density for fast ignition

R. Betti and C. Zhou, Phys. Plasmas 12, 110702 (2005);
D. Clark and M. Tabak, APS-DPP bulletin (2006)
S. Atzeni, EPS (2006)

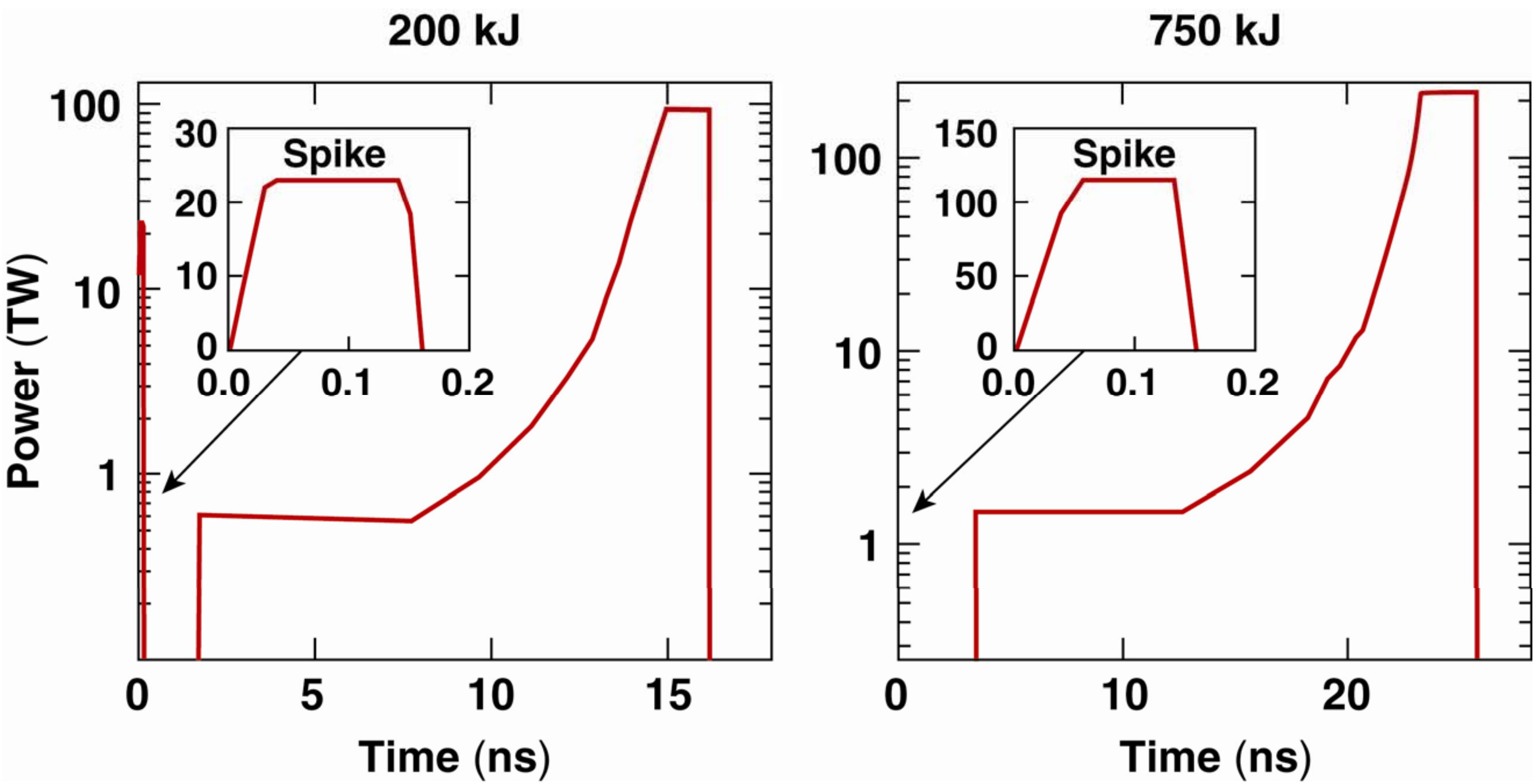
Target designs for direct-drive fast ignition use massive wetted foam shells insensitive to fluid instability



$\rho R \approx 3 g/cm^2$ $\rho R \approx 1.9 g/cm^2$ $\rho R \approx 0.7 g/cm^2$

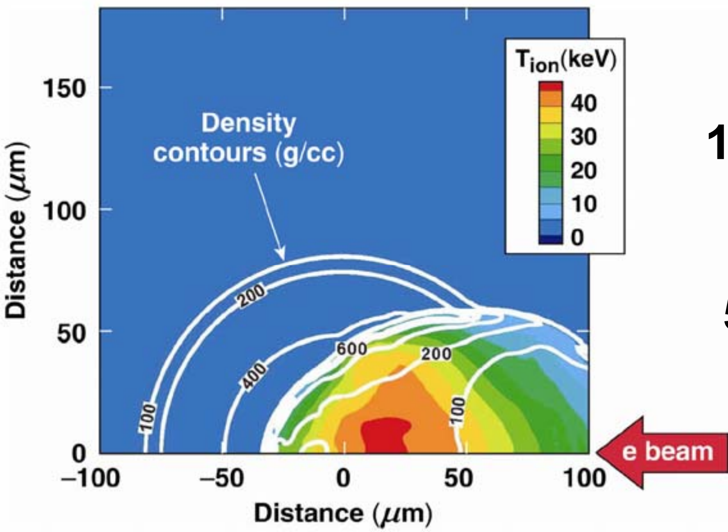
$<\rho> \approx 300\text{-}500 g/cm^3$

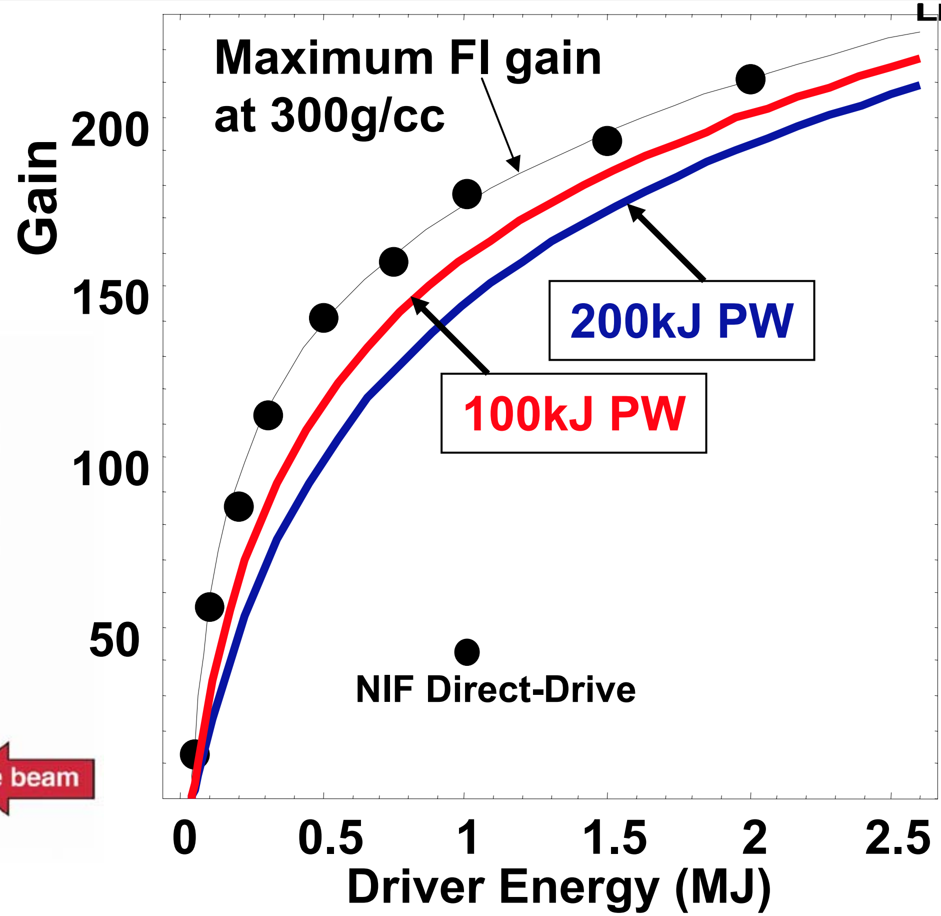
Fast-ignition targets require long laser pulses and high contrast ratios (~100 to 150) within the capabilities of the NIF



2D hydro-simulations of ignition by fast electrons and burn propagation yield fast ignition gain curves

- 2D simulations of ignition and burn by 15kJ, 2MeV, 20μm, 10ps e-beam

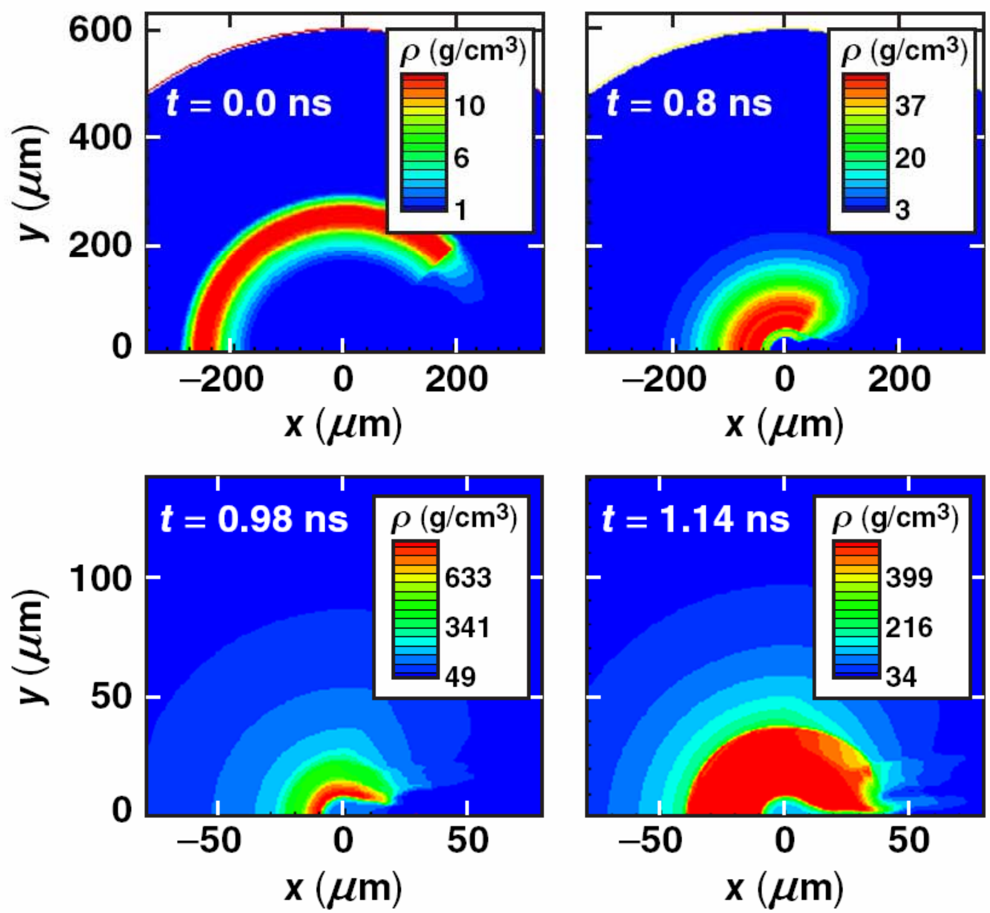


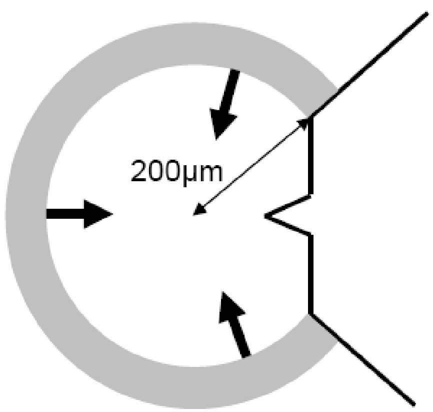


FI allows for significant gains with a few hundred kJ laser driver

Cone target implosions are simulated assuming that the cone walls are rigid and truncated at a given distance from the center

300-kJ target

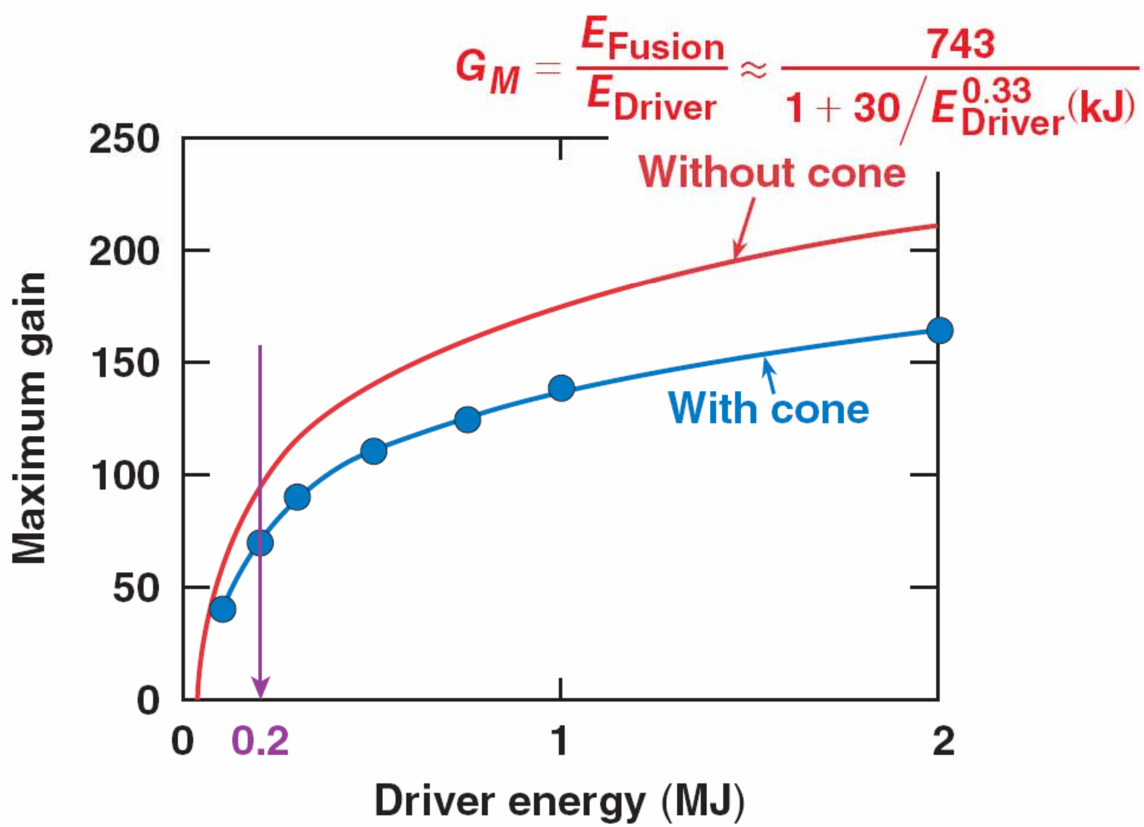




TC7651

Ignition simulations indicate that the minimum ignition energy is only weakly affected and the gain is reduced by 20% to 30%

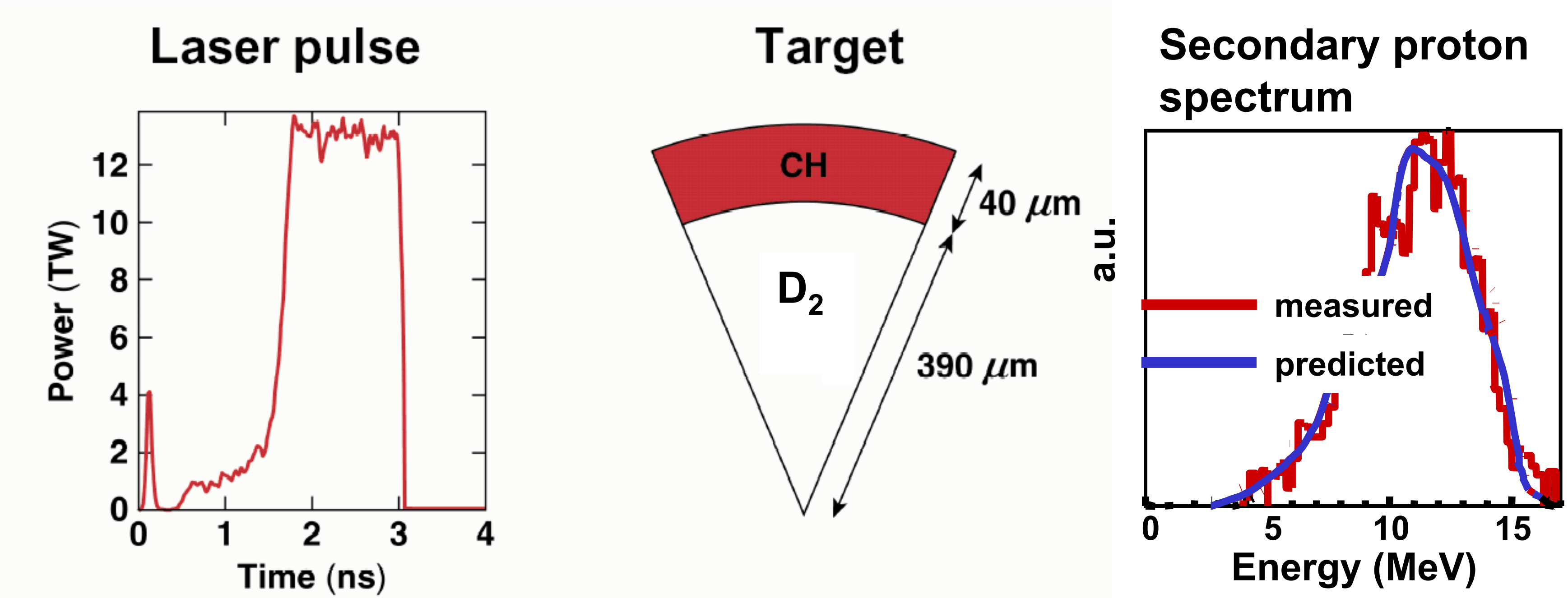
FSC UR LLE



TC7652

Slow implosions with low adiabat were tested on OMEGA D-^{3}He fusion proton energy loss measured the high ρR

$E_L \approx 20$kJ   P≈25atm $\alpha \approx 1.3$ $V \approx 2 \cdot 10^7$cm/s



- Peak ρR is 0.26g/cm^2, the highest ρR to date on OMEGA
- Empty shells would achieve ρR≈0.7g/cm^2 and stop 4MeV electrons

C. Zhou, W. Theobald, R. Betti, P.B. Radha, V. Smalyuk, *et al*, Phys. Rev. Lett. 98: 025004 (2007)

Electron generation and transport

According to the ponderomotive scaling, ignition laser pulses can produce electrons with E>>1MeV that are not stopped in the dense core

Ponderomotive temperature scaling:[1] $\left\langle E_{\text{hot}} \right\rangle = \left(\dfrac{I(\lambda/1.054\mu\text{m})^2}{10^{19}\,\text{W cm}^{-2}} \right)^{1/2} \text{MeV}$

Electron range: $R = 0.6 \times \left\langle E_{\text{hot}} \right\rangle \ \text{g/cm}^2$

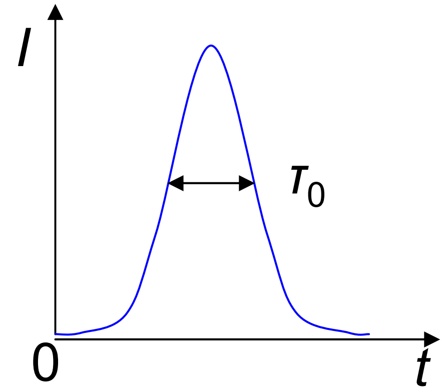
E_{hot}>>1→ Electron range greatly exceeds the optimal range for fast ignition

[1] S.C. Wilks et al., Phys. Rev. Lett. 69, 1383 (1992)
[2] S. Atzeni, Phys. Plasmas 6, 3316 (1999)

The minimum laser energy for ignition exceeds 100 kJ for λ_L=1.05 µm

Simulations:

- **Gaussian laser pulses**
- **Maxwellian electrons**



300 kJ target $\lambda = 1.054\ \mu\mathrm{m}:$

η_{PW}	r_0 (µm)	τ_0 (ps)	Min. PW laser energy (kJ)	Electron beam energy (kJ)	$\langle E_{hot} \rangle$ (MeV)	E-beam – fuel coupl. eff.
0.3	26	16	235	71	7.6	0.69
0.5	23	14	105	53	6	0.76

Frequency doubling reduces the electron mean energy, stopping length and the minimum energy for ignition[1]

$$\langle E_{\rm hot} \rangle = \left(\frac{I(\lambda/1.054\mu\text{m})^2}{10^{19}\,\text{W cm}^{-2}} \right)^{1/2} \text{MeV}$$

300 kJ target $\lambda = 0.527\ \mu\text{m}:$

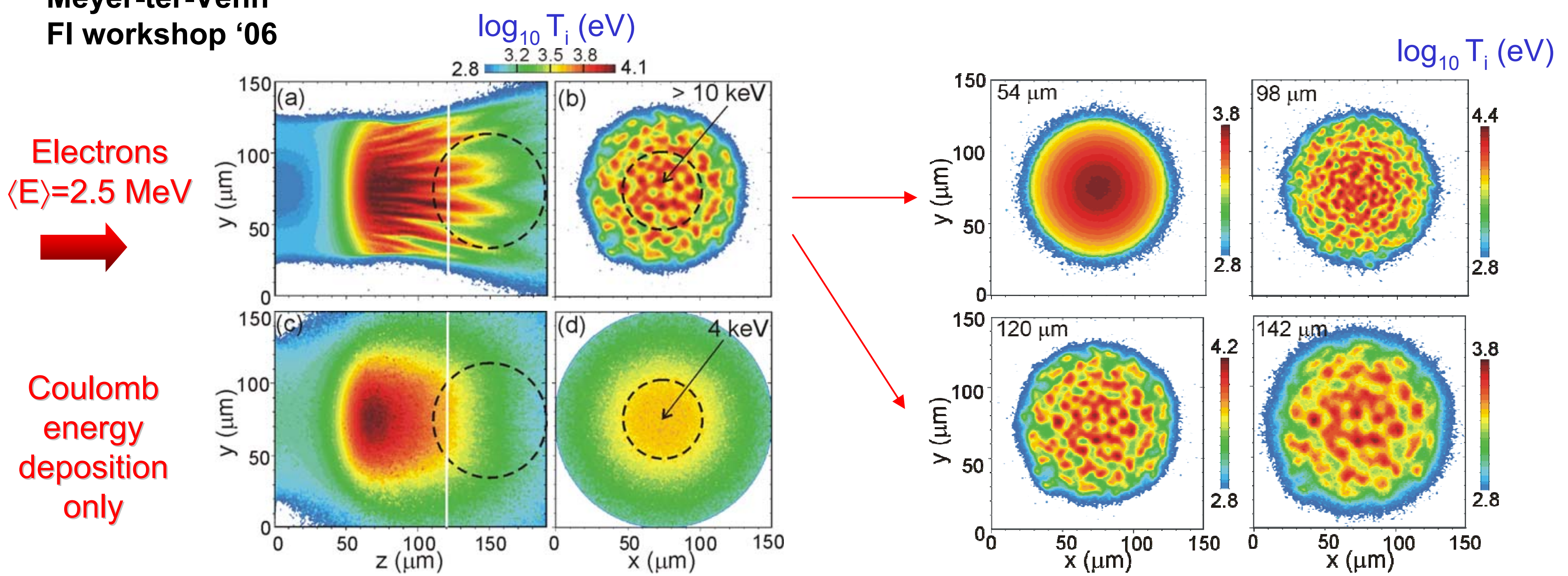
$\eta_{\rm PW}$	r_0 (μm)	τ_0 (ps)	Min. PW laser energy (kJ)	Electron beam energy (kJ)	$<E_{\rm hot}>$ (MeV)	E-beam – fuel coupl. eff.
0.3	19	8	106 (235)	32	4.8	0.86
0.5	16.8	7	50 (105)	25	3.9	0.92

[1] Also suggested in: S. Atzeni and M. Tabak, Plasma Phys. Controll. Fusion **47**, B769 (2005)

Beam filamentation develops in the low-density plasma. The e-beam energy required for ignition is 60kJ.

Honrubia and Meyer-ter-Vehn FI workshop '06

Ion temperature at the end of the pulse



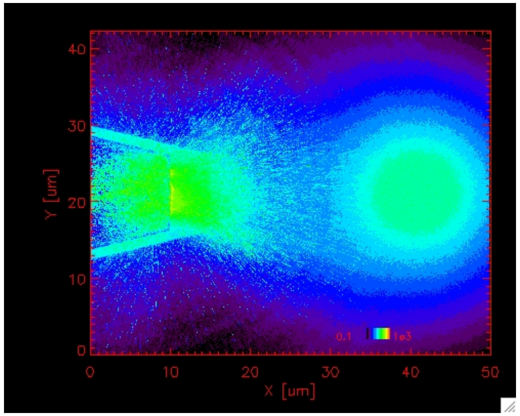
- ➢ Heating of the dense core is almost exclusively by Coulomb energy deposition.
- ➢ Self-generated fields are very important for core heating indirectly by beam filamentation and collimation.
- ➢ Ohmic heating dominates in the halo, heating it up to very high temperatures.
- ➢ Anomalous stopping not important in the dense core because
- ➢ **The e-beam has 40mic radius, 23° divergence, <E>=2.5MeV , 60kJ of total energy**

Full PIC integrated simulations of cone-guided fast ignition are carried out with PICLS

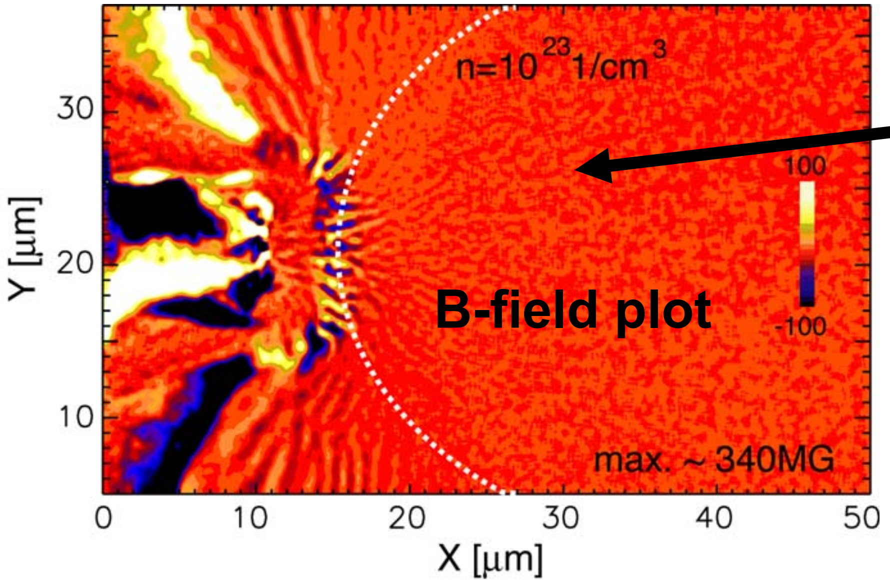
FSC

Nevada Terawatt Facility

Electron density plots



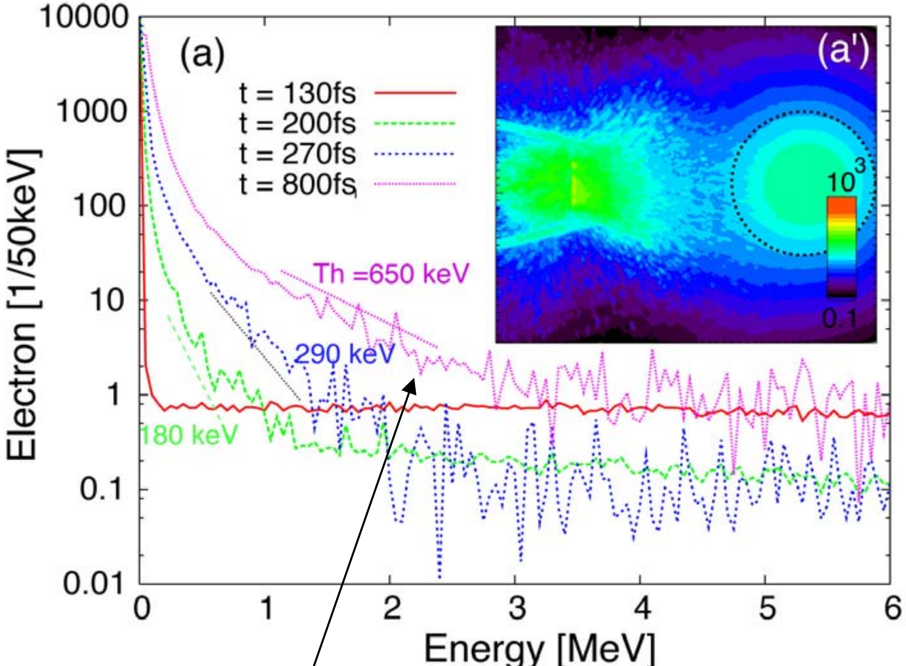
Integrated simulations of ignition-scale FI cone-targets ('08-'09).
Integrated experiments on Ω-EP ('09)

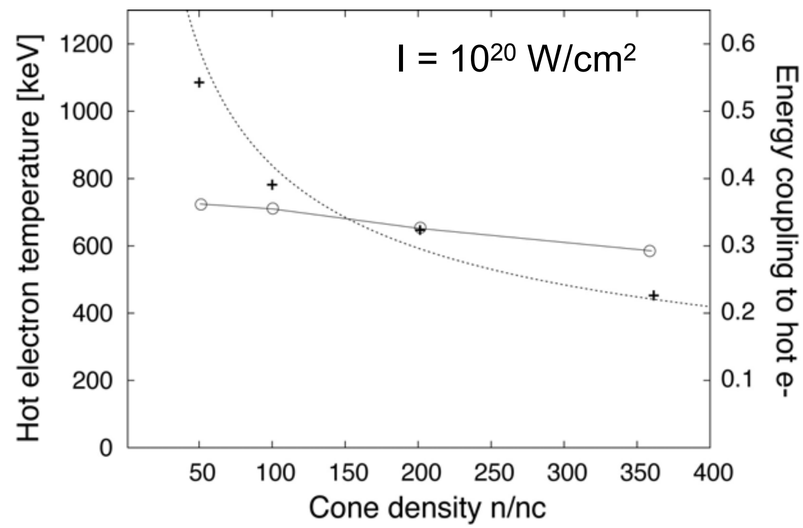


No large magnetic fields are present in the dense plasma. The hot electron stopping is collisional.

Sentoku, Cowan, Crisman (UNR)

PICLS simulations show that the hot-electron energy is less than predicted by the ponderomotive scaling





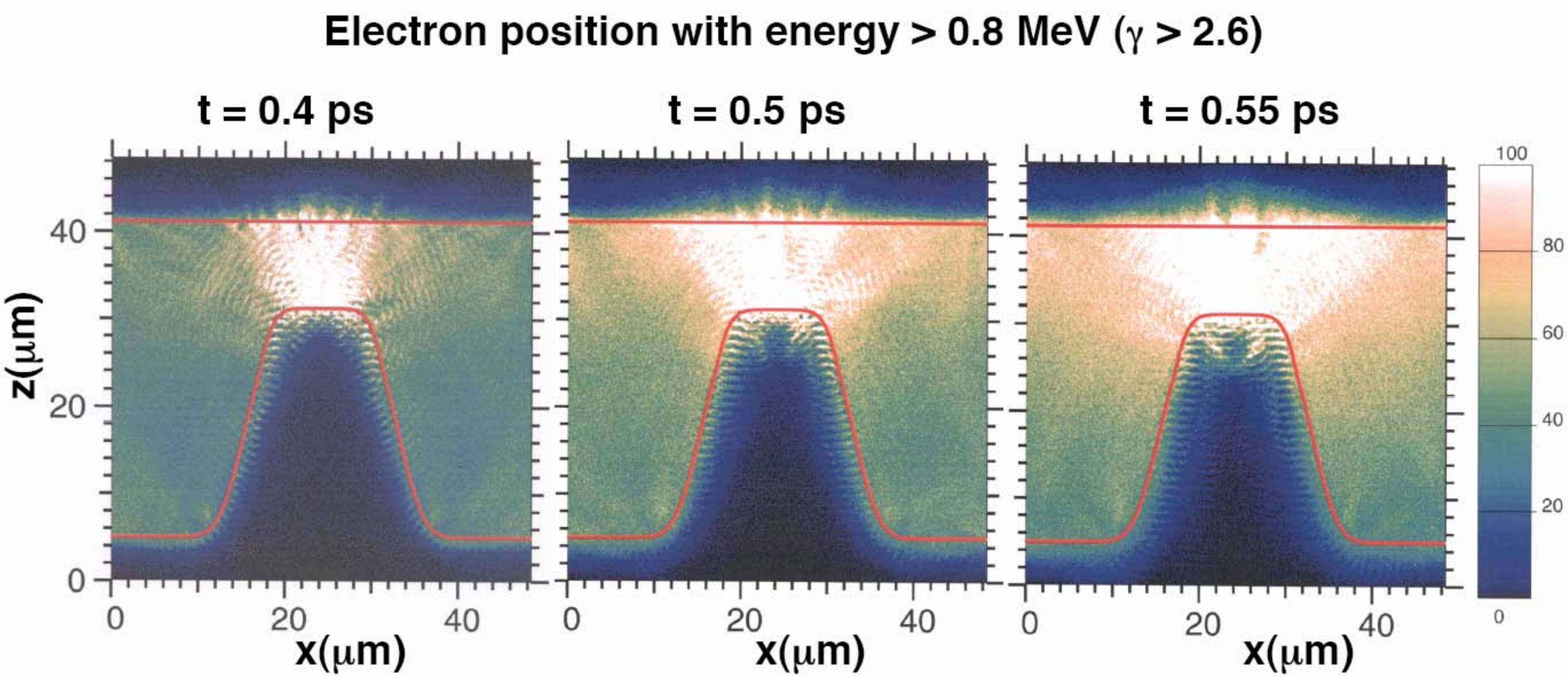
The energy of the hot-electrons reaching the core is ≤ 1MeV

Higher cone densities lead to less energetic electrons

Sentoku, Cowan, Crisman (UNR)

A wide angular spread of the hot electrons is observed in PIC simulations with Z3

2-D, 10^{19} W/cm^2, p-polarization, $16n_c$, T_e = 10 keV

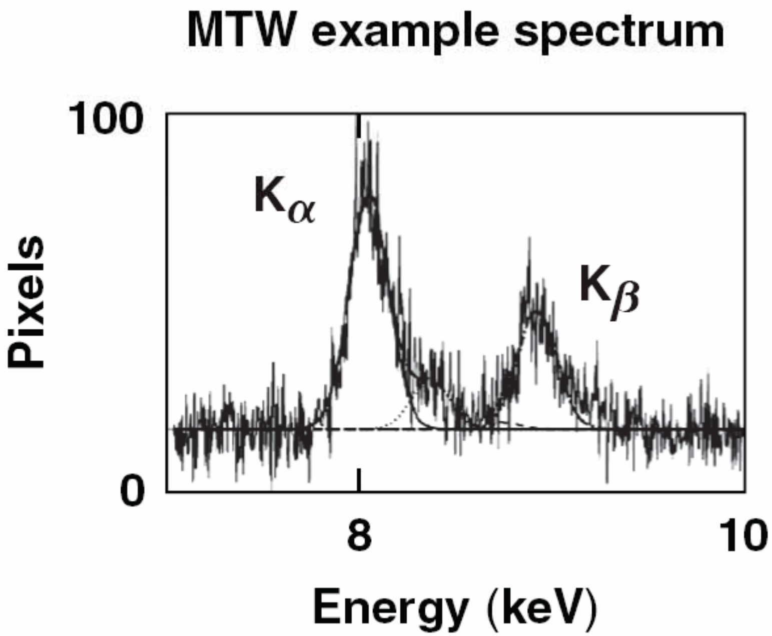


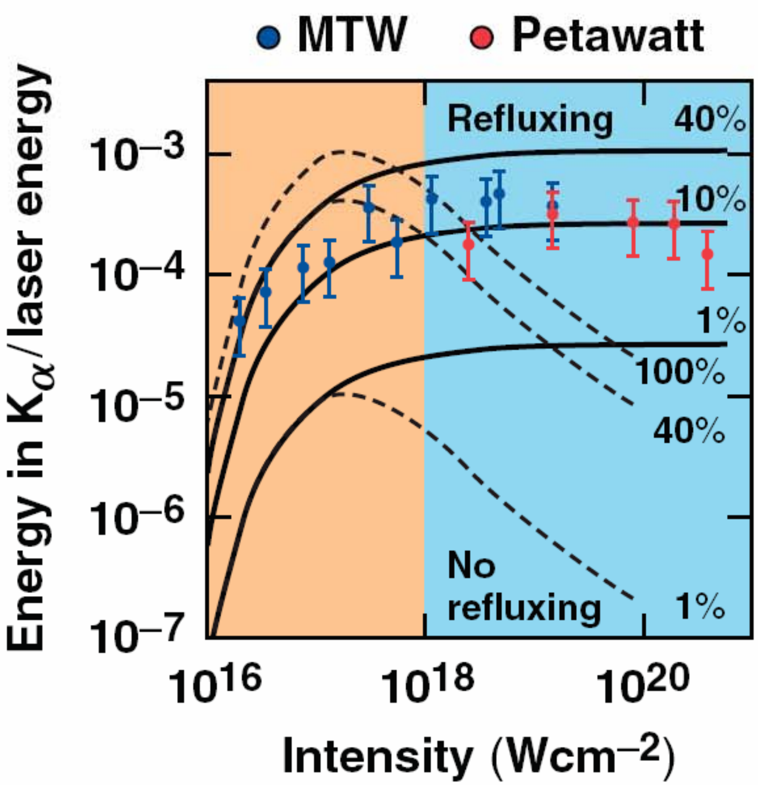
Over 50% of the laser energy is converted into hot electrons, twice the absorption of a planar target

Lasinski, Town, Langdon, Still, Tabak et al, FI Workshop 2006

K-shell emission measurements are consistent with a re-circulating electron model and $\eta_{L \rightarrow e} \approx 10\%$ to 30% for $I > 10^{18}$ Wcm^{-2}

Copper target: $500 \times 500 \times 20$ μm
MTW laser pulse: 1 J, 1 ps





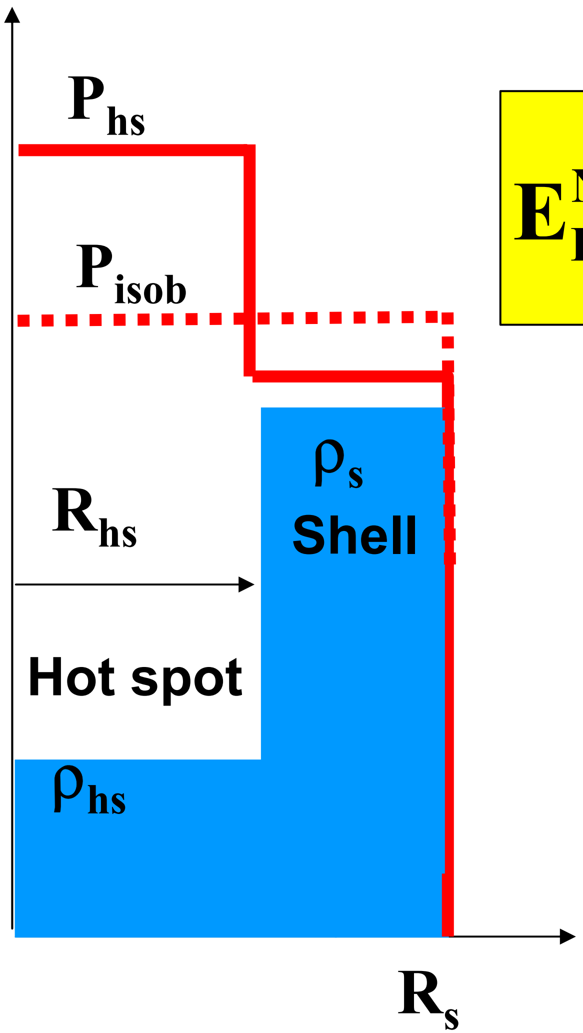
P. Nilson et al (FSC/LLE)

E15598

$$T_{hot} = 0.511\left[\left(1 + I_{18}\lambda^2_{\mu m}/1.37\right)^{1/2} - 1\right] \text{ valid}$$

SHOCK IGNITION

The ignition energy is lower in a non-isobaric fuel assembly

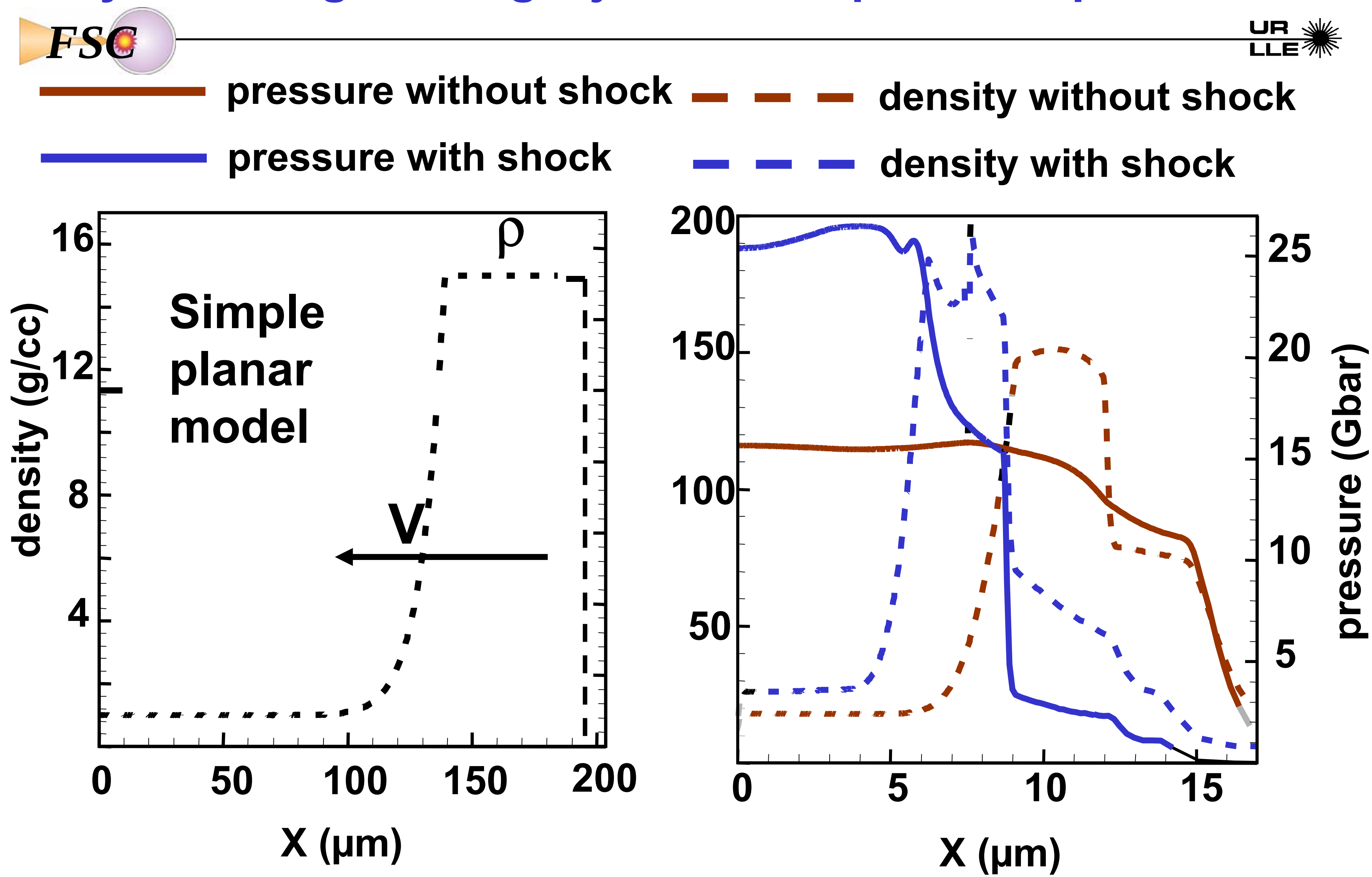


$$E_{Laser}^{NON\text{-}isob.\text{-}ign.} \sim \frac{E_{Laser}^{isob.\text{-}ign.}}{\Phi} + \Delta E^{non\text{-}isob}$$

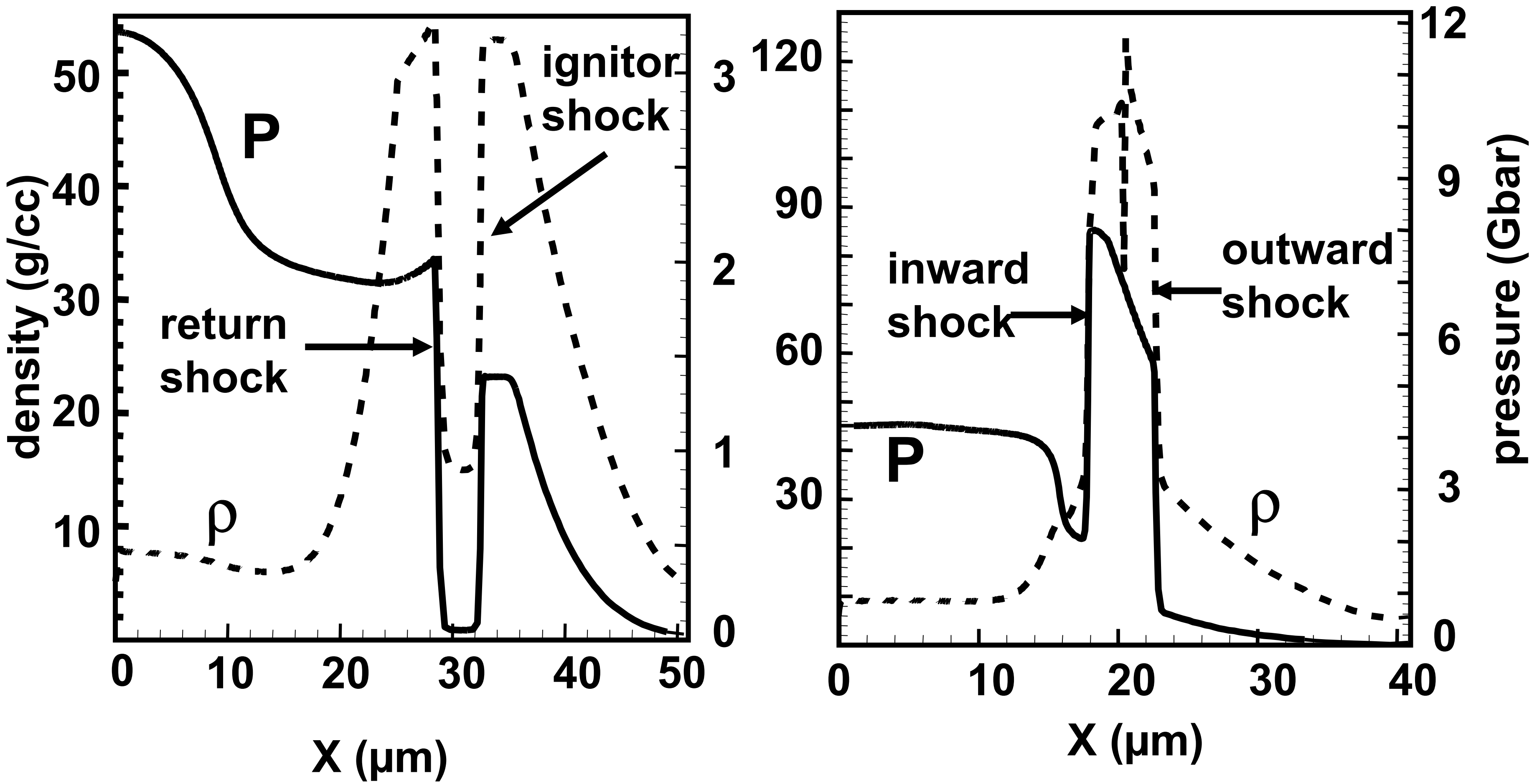
For adiabatic compression of the hot spot

$$\Phi \approx \left(\frac{P_{hs}}{P_{iso}} \right)^3$$

A non-isobaric fuel assembly can be produced by shocking the target just before peak compression

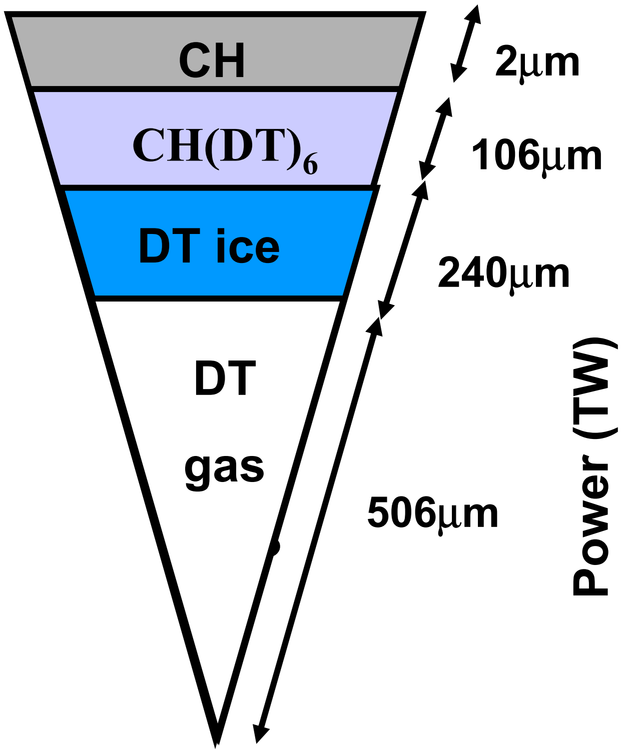


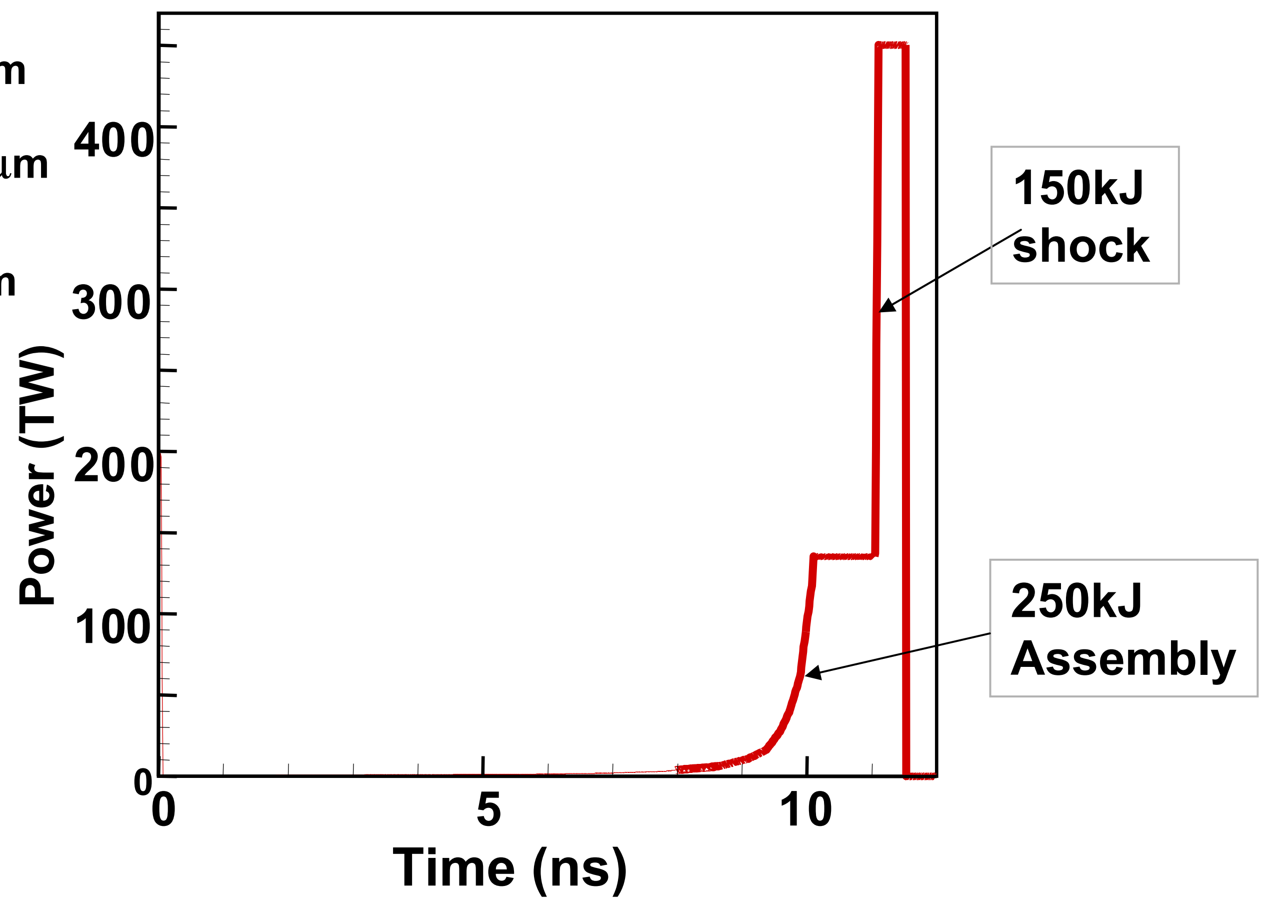
Producing a non-isobaric assembly requires the collision of the ignitor shock with the return shock



The ignitor shock can be launched with a spike of the laser intensity or particle beams

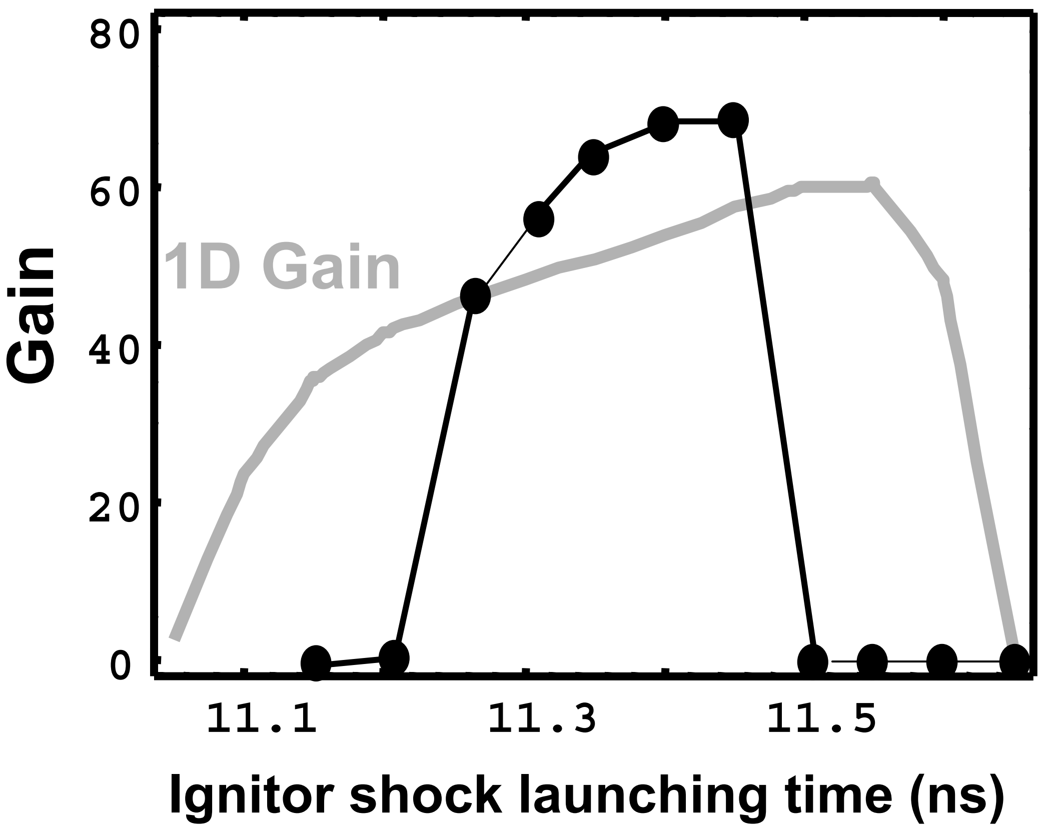
E_L=400kJ, V_i=2.4e7cm/s, α=0.7-1, λ_L=0.35μm





Minimum shock energy for ignition = 50kJ, total energy = 300kJ

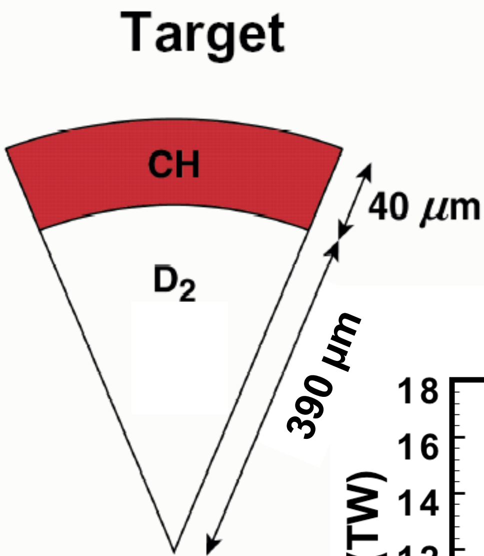
The robustness of the ignition is measured by the size of the shock ignition window



- 2D simulations
  Modes l=4-100,
  NIF 2D-SSD
  Energy = 400kJ
  Normal Incidence
  Thomas-Fermi EOS
  No radiation

Significant gains are predicted with moderate driver energies

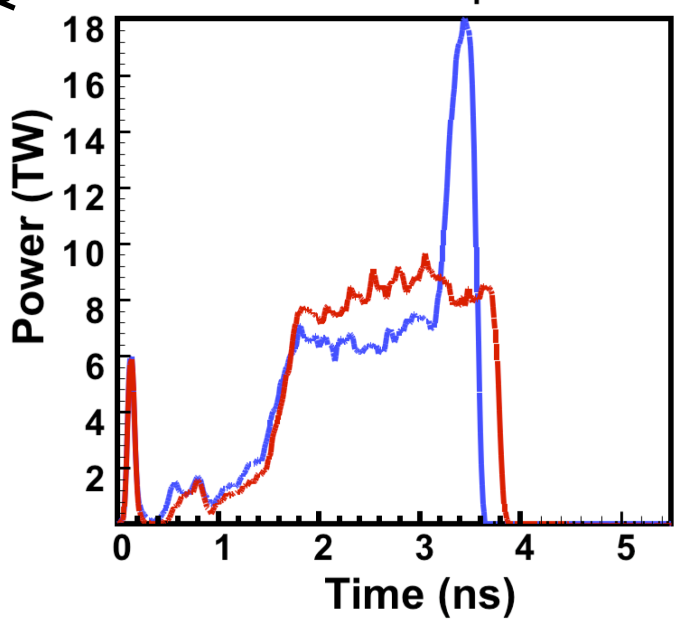
The shock ignition concept has been tested on OMEGA

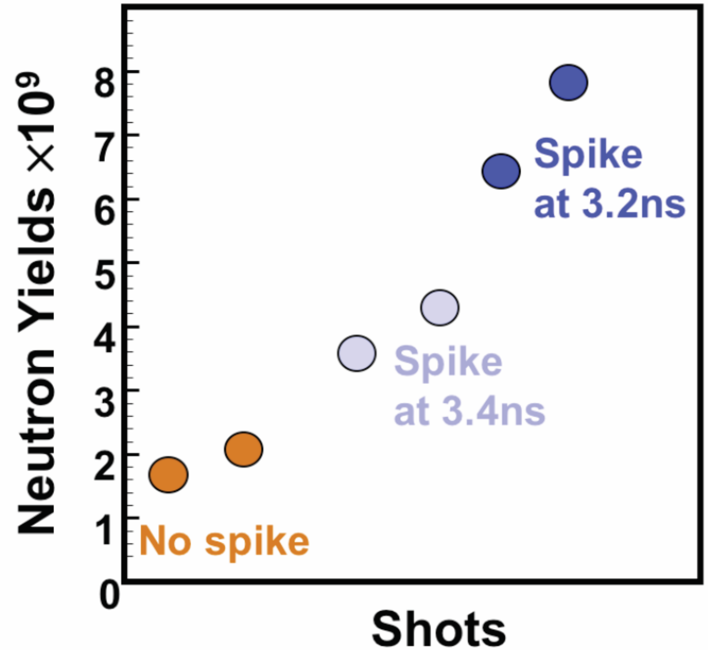


W. Theobald,,
C. Zhou,
et al
(UR-LLE)

E_L=17-18kJ
$\alpha \approx 1.3$

Pulse shape with and without shock spike





The neutron yield increases considerably when a shock is launched at the end of the pulse

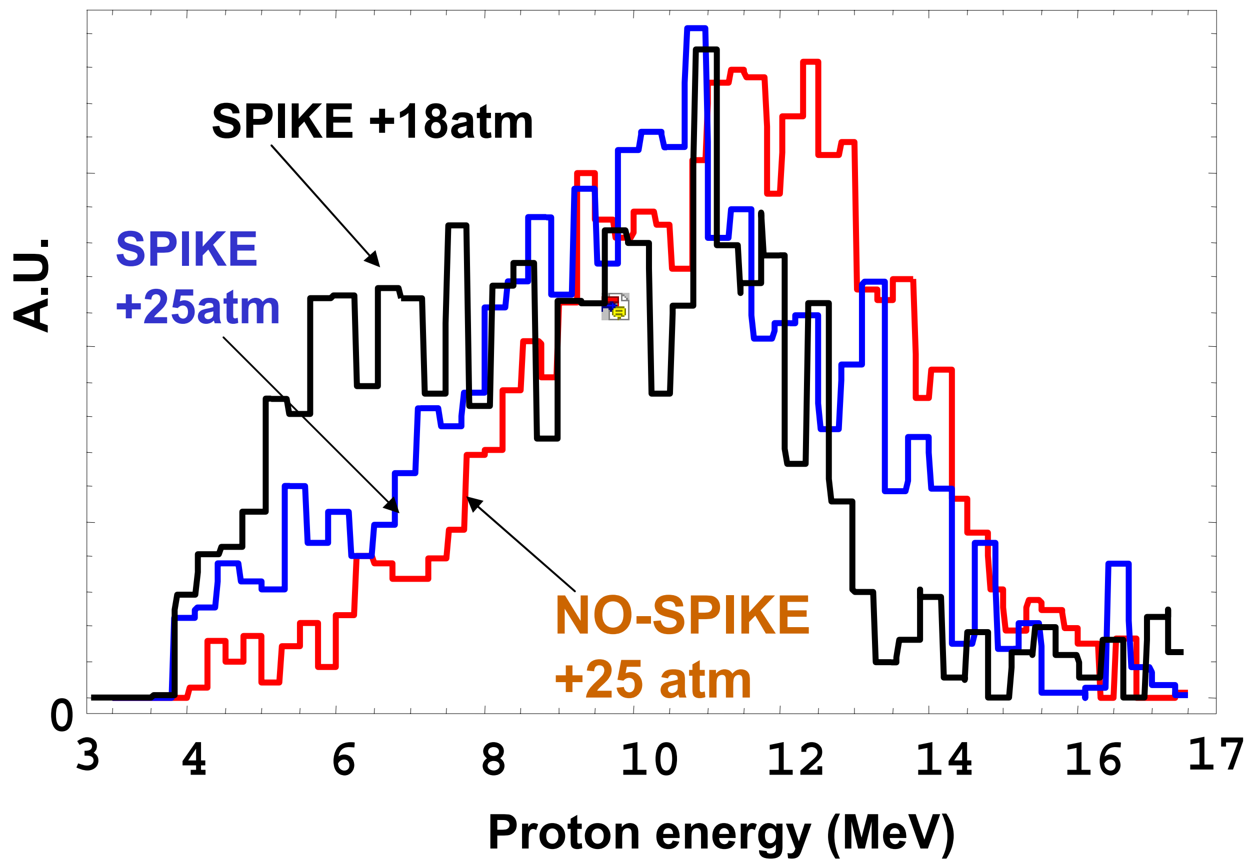
The core is more compressed for pulse shapes with a spike

Shot→No-spike- 20.5kJ-25atm D2- <ρR>= 0.15g/cm², Max- ρR=0.26g/cm² → Highest ρR on OMEGA up to 2006

Shot→with spike - 17kJ-25atm D2-<ρR>= 0.17g/cm²

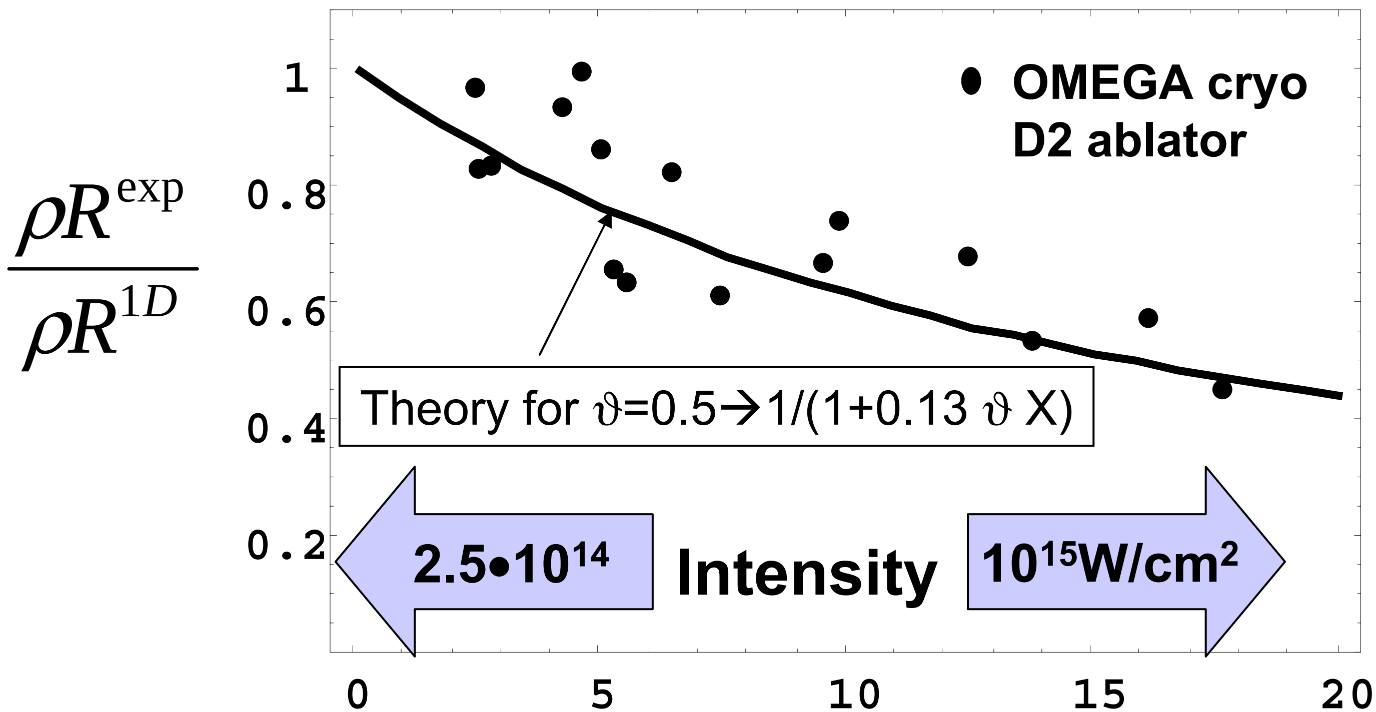
Shot→with spike - 17kJ-18atm D2-<ρR>= 0.20g/cm²

Secondary proton spectra from D+ ^{3}He fusion



There are indications of hot electron preheat in cryogenic ablators for 3ω Direct Drive

ρR degradation in OMEGA in cryo D2 ablator

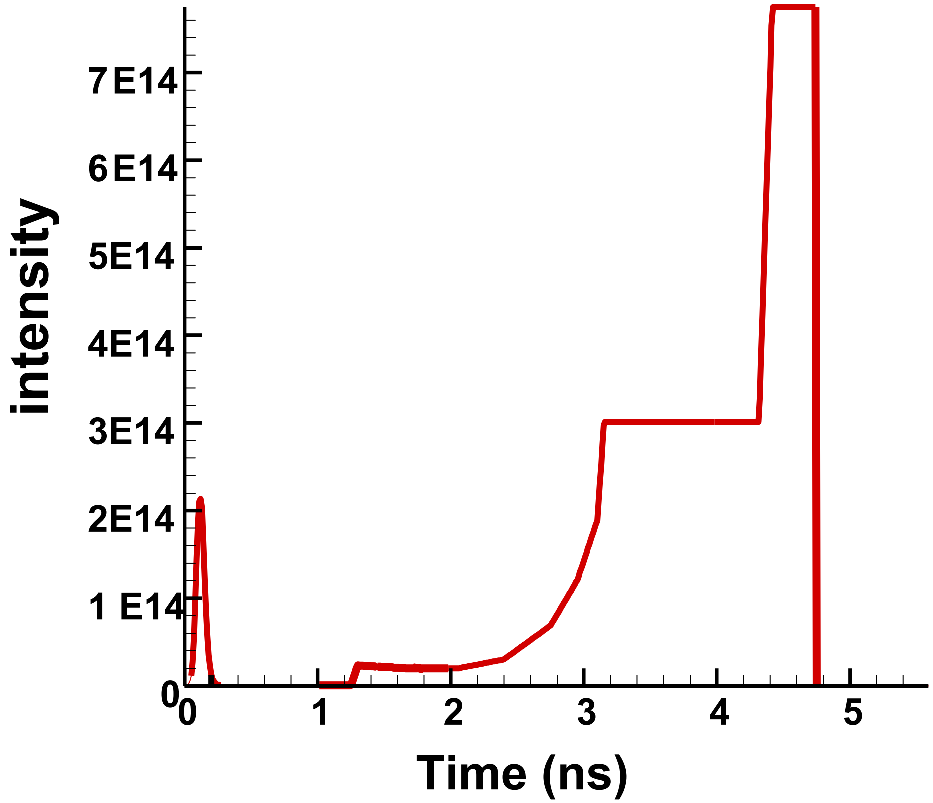


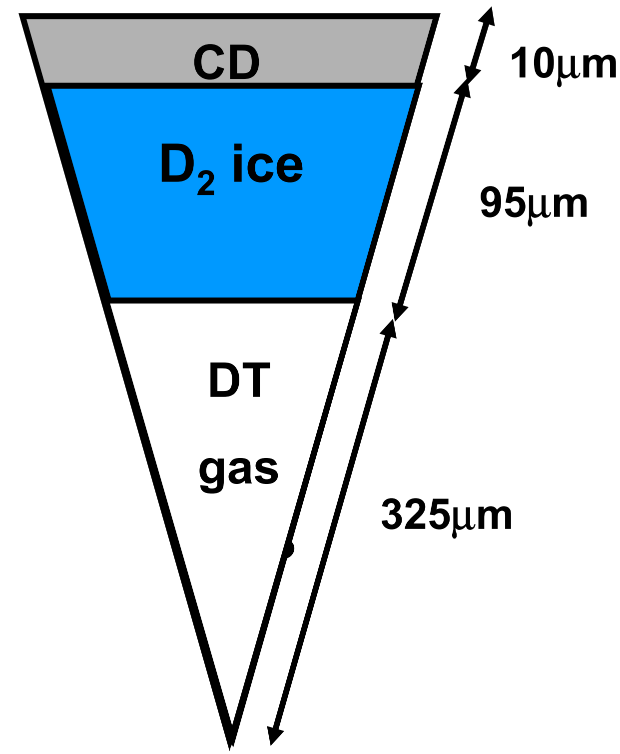
$$\frac{H(J)}{\alpha^{0.6}E_L(kJ)}\left(\frac{V_i(cm/s)}{10^7}\right)^{1.25}$$

Smalyuk et al
LLE

H(J)= energy deposited by hot electrons

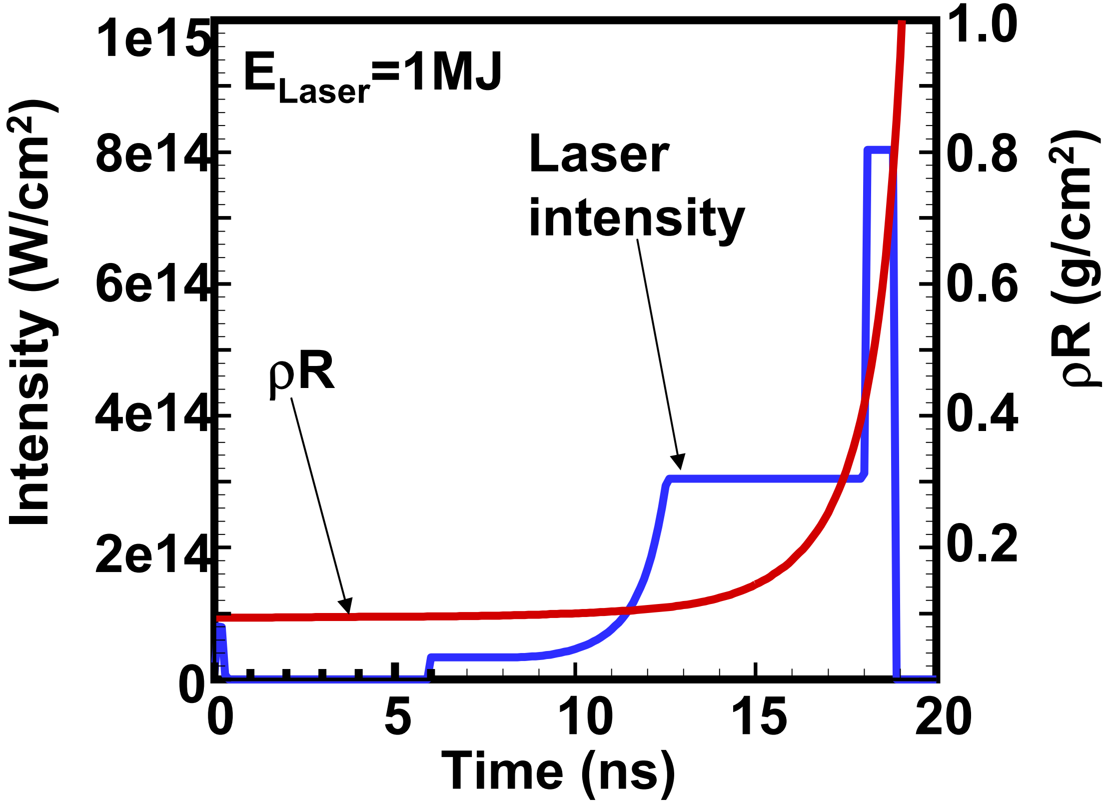
Cryo shock ignition on OMEGA requires a thick (10μm) CD overcoat and low intensities to minimize preheating during the assembly and spike pulse

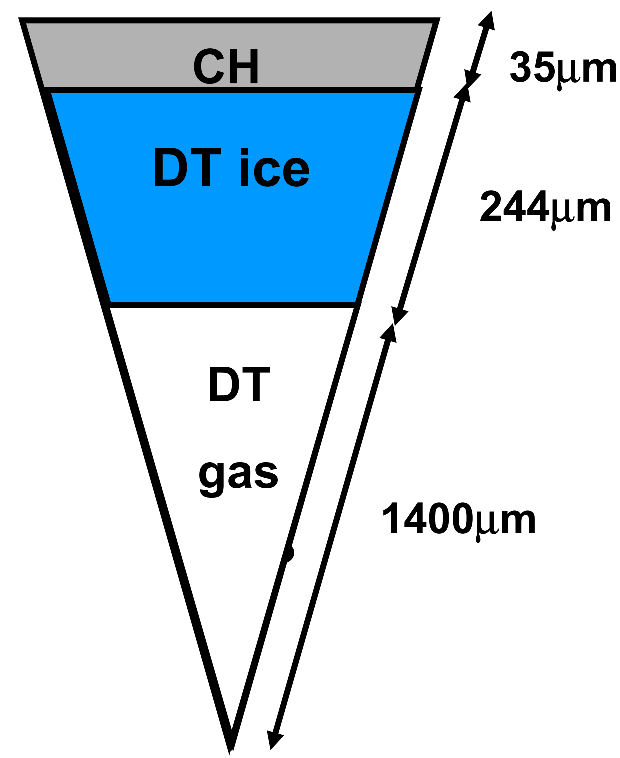




E_{Laser}=18kJ, α=1.3, ρR_{max}=360mg/cm^2, 1D Yield = 2.2e11

CH-Ablator 1MJ shock-ignition design at low laser intensity for preheat reduction during assembly pulse





V_I=2.1e7cm/s, IFAR=30, α=0.7, 1D Gain=142
rhoR during spike=40-80mg/cm^2
e- (100keV) rhoR penetration =17mg/cm^2

ISSUES/QUESTIONS AND PLANS

FAST IGNITION FUEL ASSEMBLY

- Perform Warm (CH) low-V_i low-α cone-target implosions in '08

→Diagnose core conditions (areal density)

→Diagnose cone conditions (integrity, cone/target mixing)

- Perform Cryogenic FI implosions on OMEGA/FIREX (2009-2010?)

FAST IGNITION ELECTRON TRANPORT

- Perform fast electron transport in relevant FI plasmas on OMEGA-EP AND FIREX
- Answer relevant questions/issues such as:

What is the fast electron energy reaching the core?

What is the fast electron divergence?

Estimate the PW laser energy required for ignition

SHOCK IGNITION

- Perform cryogenic shock-ignition implosions on OMEGA ('07-'08)

Answer relevant questions/issues such as:

Can the shock be driven by fast particles (such as hot electrons)?

Can shock ignition help direct drive if preheat is an issue on the NIF?

Is shock ignition more attractive with KrF lasers?

UCRL-PRES-230880

Heavy Ion Fusion Science/Warm Dense Matter/ Hydrodynamics experiments using ion beams

John Barnard (LLNL)

on behalf of

The Heavy Ion Fusion Science Virtual National Laboratory

IFE Science and Technology Strategic Planning Workshop
San Ramon, California
April 24-27, 2007

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Berkeley and Lawrence Livermore National Laboratories under Contract Numbers DE-AC02-05CH1123 and W-7405-Eng-48.

What are the HIFS/WDM/Hydro experiments?

Heavy Ion Fusion Science experiments:

The physics of compressing beams in space and time

-- Drift compression and final focus

-- High brightness beam preservation

-- Electron cloud/halo/ and non-linear processes

Warm Dense Matter (WDM) experiments

-- Equation of state

-- Two-phase regime and droplet formation

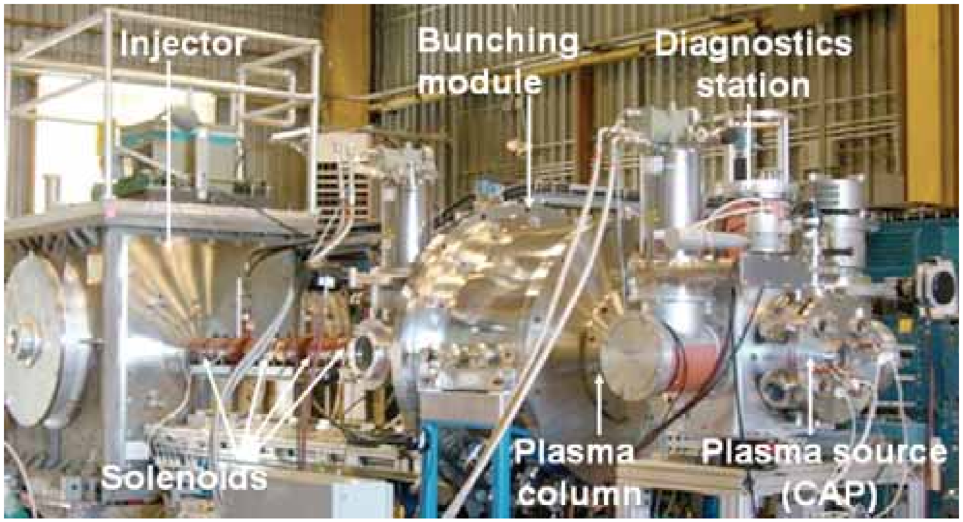
-- Insulator and metals at WDM conditions

Hydrodynamics experiments relevant to HIF targets

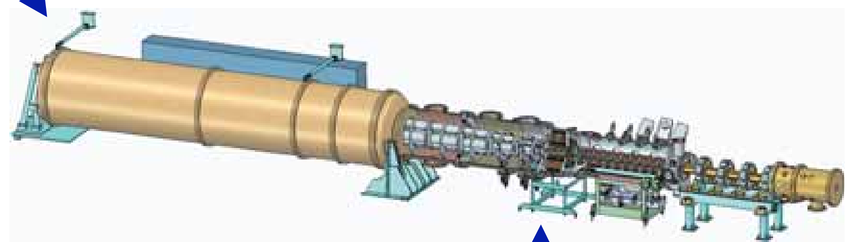
-- Hydro stability, volumetric ion deposition and Rayleigh Taylor mitigation techniques

UCRL-PRES-230880

The HIFS VNL has developed a plan for using present and future accelerators for WDM and HIF experiments



Today:



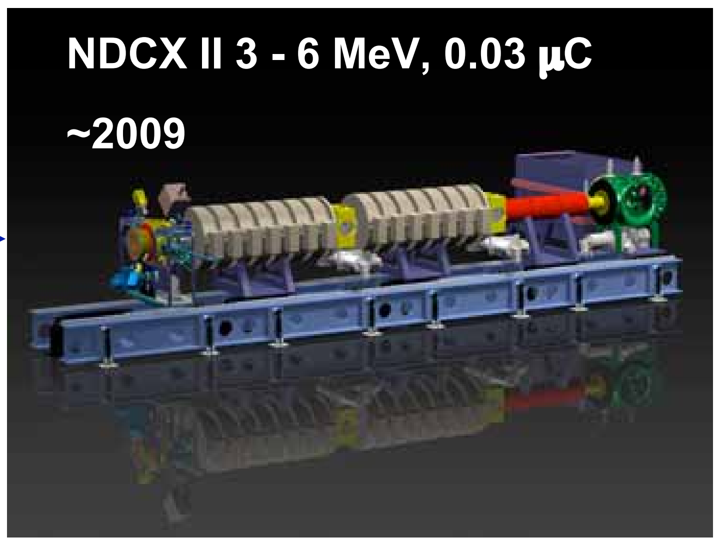
NDCX I

0.4 MeV, 0.003 μC

HCX

1.7 MeV, ~0.025 μC

Soon



Future

IB-HEDPX (with CD0)
5 - 15 year goal
20 - 40 MeV, 0.3 - 1.0 μC
WDM User facility

10 kJ Machine for HIF
10 - 20 year goal
Target implosion physics

HIF/WDM beam science: neutralized focusing and drift compression are now being tested for use in WDM and HIF

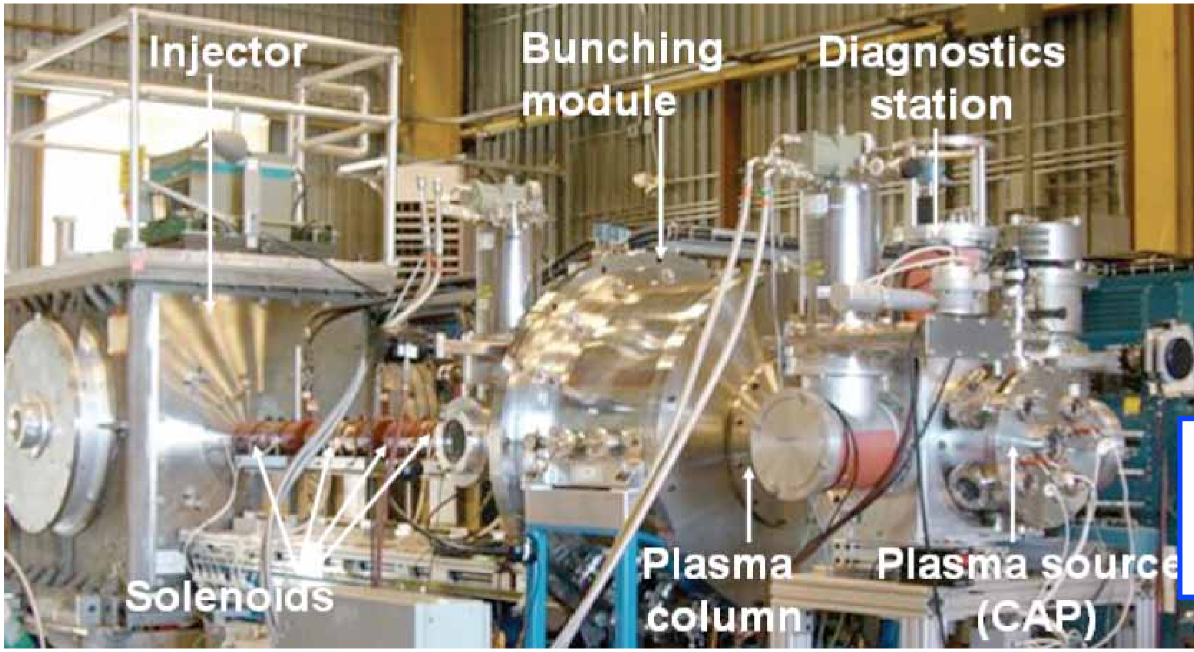
Both techniques virtually eliminate the repulsive effects of space charge on transverse and longitudinal compression

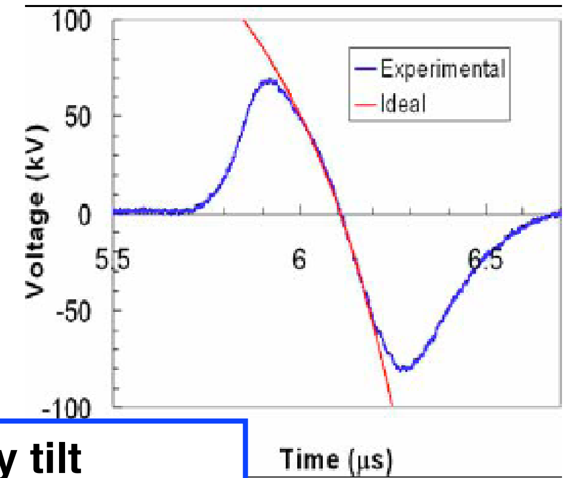
Transverse compression (= focusing the beam to a small spot, raising the watts/cm^2): Recent VNL experiments, eg. scaled final focus experiment, (MacLaren et al 2002), NTX (Roy et al 2004), and current NDCX-1 have demonstrated benefits of neutralization by plasmas, also required for HIF.

Longitudinal compression (= raising the watts): WDM experiments require very short, intense pulses (<~ 1 ns) (shorter than needed for HIF). Neutralization allows high current/high power beams. Modular HIF concept also pushes limit of high current.

UCRL-PRES-230880

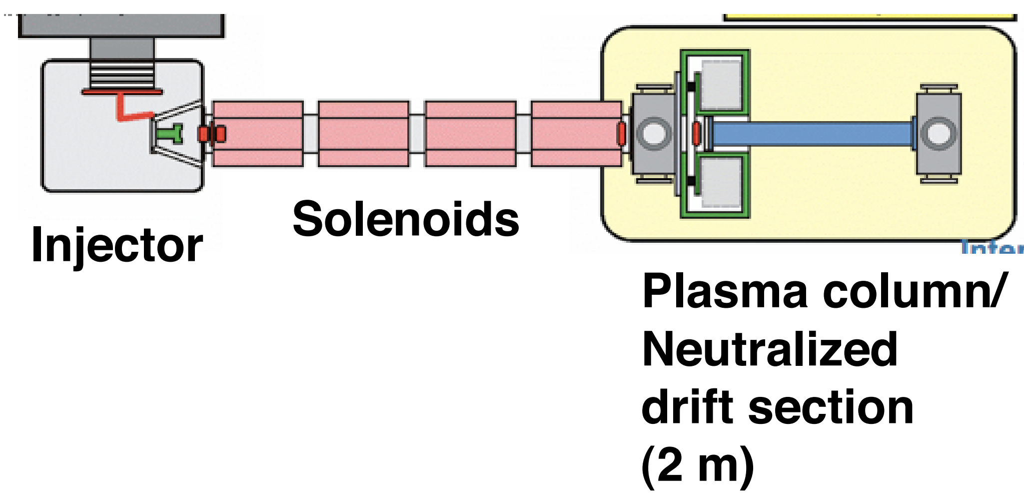
NDCX-1 has demonstrated > factor 70 pulse compression, and kinematically limited spot radius

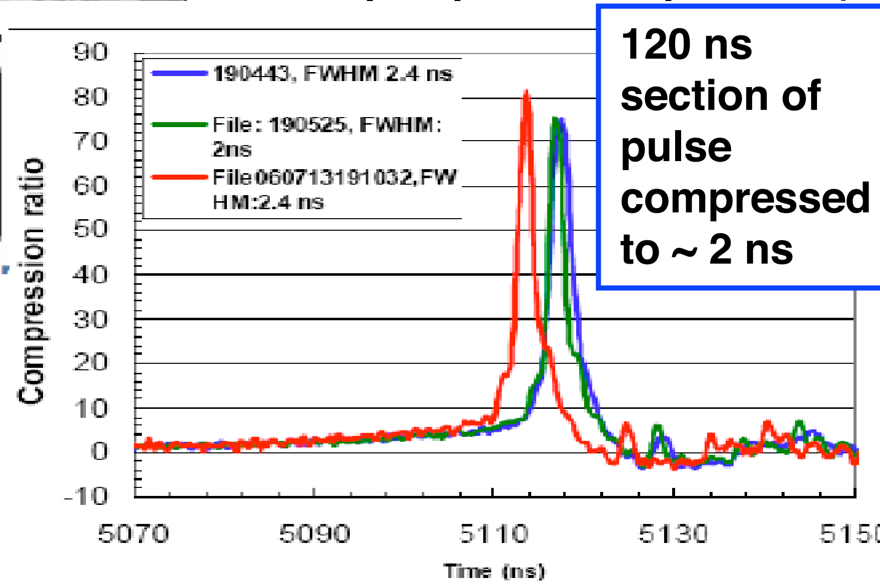




Velocity tilt accelerates tail, decelerates head

(Like chirped pulse compression)

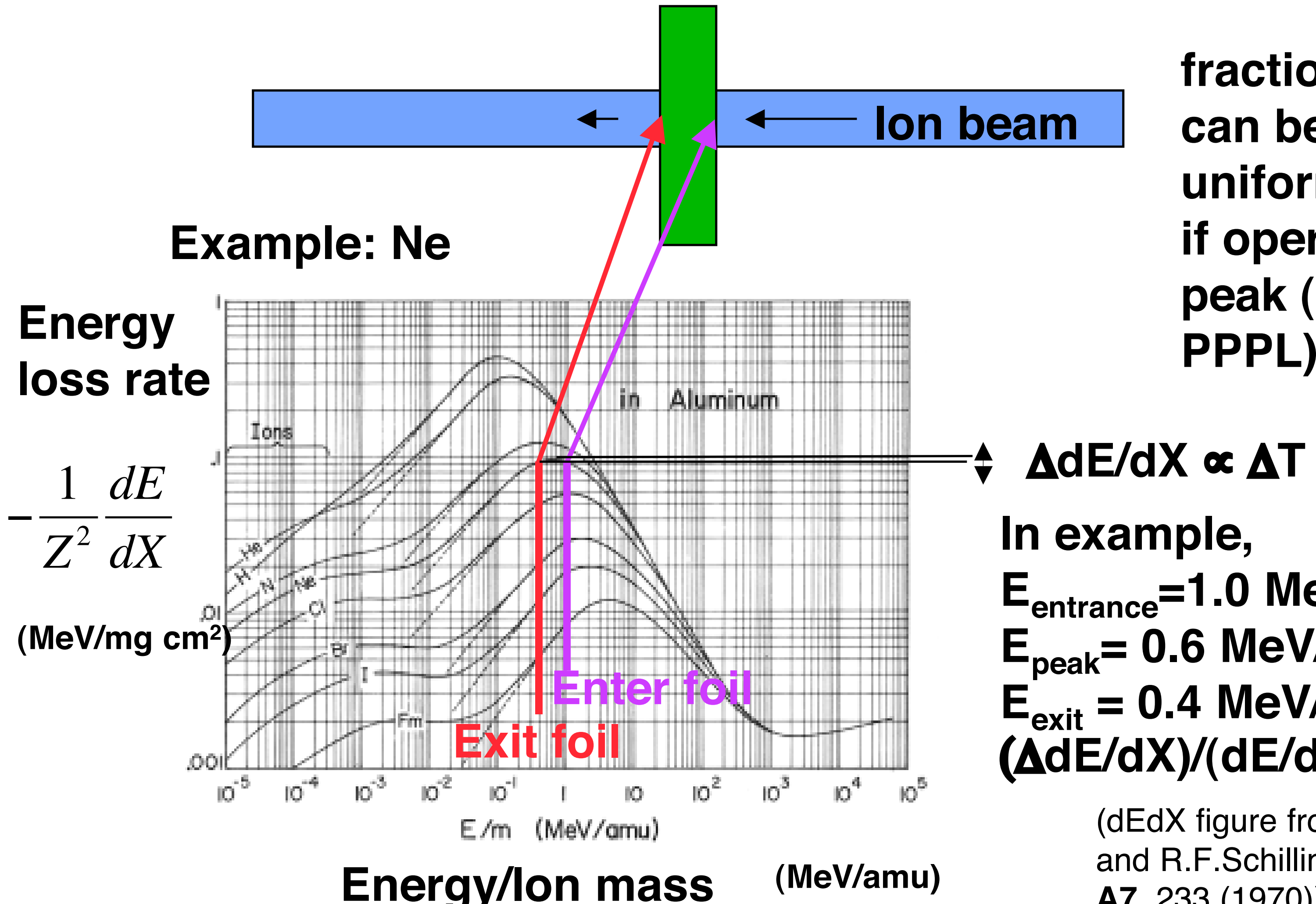




120 ns section of pulse compressed to ~ 2 ns

WDM strategy: maximize uniformity and the efficient use of beam energy by placing center of foil at Bragg peak

In simplest example, target is a foil of solid or "foam" metal



fractional energy loss can be high and uniformity also high if operate at Bragg peak (Larry Grisham, PPPL)

In example,

$E_{entrance}$=1.0 MeV/amu

E_{peak}= 0.6 MeV/amu

E_{exit} = 0.4 MeV/amu

$(\Delta dE/dX)/(dE/dX) \approx 0.05$

(dEdX figure from L.C Northcliffe and R.F.Schilling, Nuclear Data Tables, **A7**, 233 (1970))

A user facility for ion beam driven HEDP/WDM will have unique characteristics

Precise control of energy deposition

Large sample sizes compared to diagnostic resolution volumes (~ 1's to 10's μ thick by ~ 1 mm diameter)

Uniformity of energy deposition (<~ 5%)

Ability to heat all target materials (conductors and insulators, foams, powders, ...)

Pulse long enough to achieve local thermodynamic equilibrium

A benign environment for diagnostics

High shot rates (10/hour to 1/second)

Potential for multiple beamlines/target chambers

We have identified a series of warm dense matter experiments that can begin on NDCX-I at Temperature < 1 eV

	Target temp.	NDCX-1 or HCX	NDCX-2
Transient darkening emission and absorption experiment to investigate previous observations in the WDM regime	Low (0-0.4 eV)	√	
Measure target temperature using a beam compressed both radially and longitudinally	Low	√	
Thin target dE/dx, energy distribution, charge state, and scattering in a heated target	Low	√	
Positive - negative halogen ion plasma experiment	>0.4 eV	√	√
Two-phase liquid-vapor metal experiments	0.5-1.0	√	√
Critical point measurements	>1.0	?	√

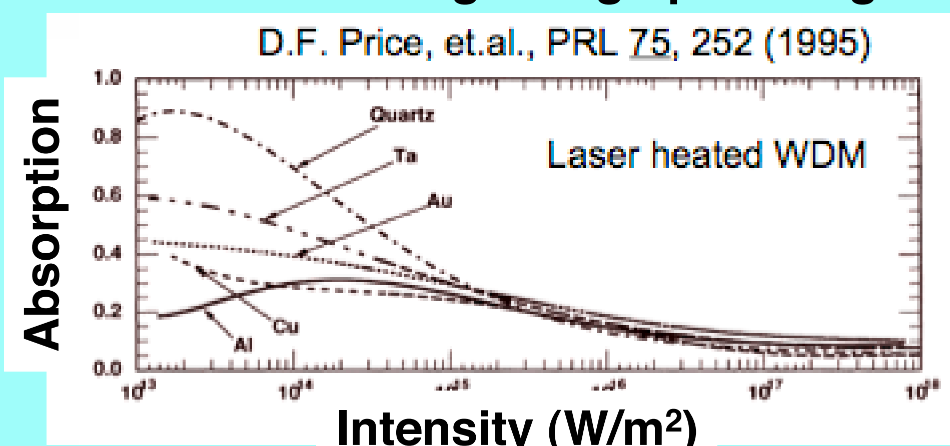
time

We have identified a unique series of warm dense matter experiments that can begin on NDCX-I at Temperature < 1 eV

	Target temp.	NDCX-1 or HCX	NDCX-2
Transient darkening emission and absorption experiment to investigate previous observations in the WDM regime	Low (0-0.4 eV)	√	

time

What is the physical mechanism for changes in the optical properties of glass, as matter approaches the WDM regime? Can these optical changes be induced from excitation by ion beams? What information is obtained from the emission? How does the darkening differ in crystalline and amorphous materials (e.g. glass vs. quartz)? Can the darkening be used for fast switching of high power light beams?



We have identified a unique series of warm dense matter experiments that can begin on NDCX-I at Temperature < 1 eV

	Target temp.	NDCX-1 or HCX	NDCX-2
Measure target temperature using a beam compressed both radially and longitudinally	**Low**	√	

Can we measure the thermodynamic properties of matter heated by ion beams compressed in space and time? **How uniform must the target temperature be for useful equation of state measurements? What are the differences between foams and solids at low T? Can we go beyond specific heat and expansion measurements to obtain liquid-vapor phase diagram, evaporation rates and EOS?**

time

We have identified a unique series of warm dense matter experiments that can begin on NDCX-I at Temperature < 1 eV

	Target temp.	NDCX-1 or HCX	NDCX-2
Thin target dE/dx, energy distribution, charge state, and scattering in a heated target	**Low**	√	

time

Can an ion beam (*after* it heats and exits a target) be used as a unique target probe for WDM exploration? How do the differences in charge state and energy loss differ between an ion beam propagating through a foam and a beam propagating through a solid of the same column density? Our ions have precisely determined E, so ion dE/dX can be accurately measured.

We have identified a unique series of warm dense matter experiments that can begin on NDCX-I at Temperature < 1 eV

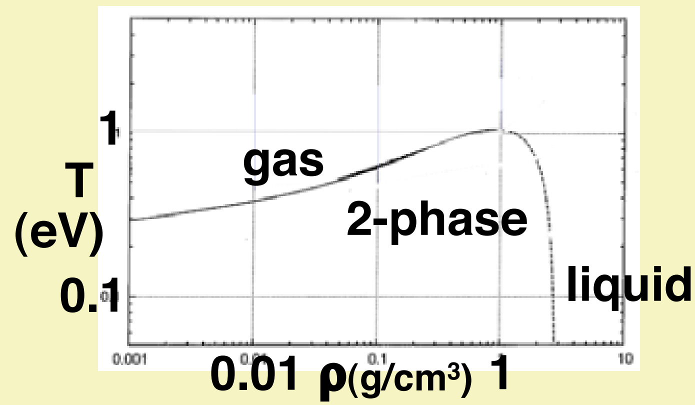
	Target temp.	NDCX-1 or HCX	NDCX-2
Can unique states of matter be created with nearly equal quantities of positive and negative ions (and few electrons)? What are the physical properties of such a state? **Is there a phase transition from low conductivity to a semiconductor? (Negative ions are like "donors" and positive ions like "acceptor" impurities.) Is there an emission (annihilation) line signature of this plasma? What are the photoconduction and junction non-linearities for these plasmas? Can these plasmas handle large current densities?**			
Positive - negative halogen ion plasma experiment	**>0.4 eV**	√	√

time

We have identified a unique series of warm dense matter experiments that can begin on NDCX-I at Temperature < 1 eV

	Target temp.	NDCX-1 or HCX	NDCX-2
Two-phase liquid-vapor metal experiments	0.5-1.0	√	√

What is the temperature-density boundary between the liquid, liquid-vapor, and vapor regime for strong (refractory) metals? **What is the equation of state (pressure as a function of temperature and density)? In the two-phase regime, what is the best way to make predictive simulations of the dynamics including the effects of droplets? (Are theory models for evaporation kinetics correct?) What determines the spectrum of droplet sizes?**

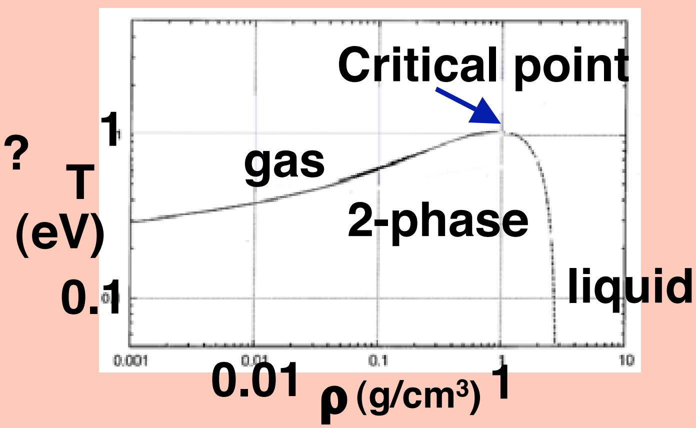


time

We have identified a unique series of warm dense matter experiments that can begin on NDCX-I at Temperature < 1 eV

	Target temp.	NDCX-1 or HCX	NDCX-2

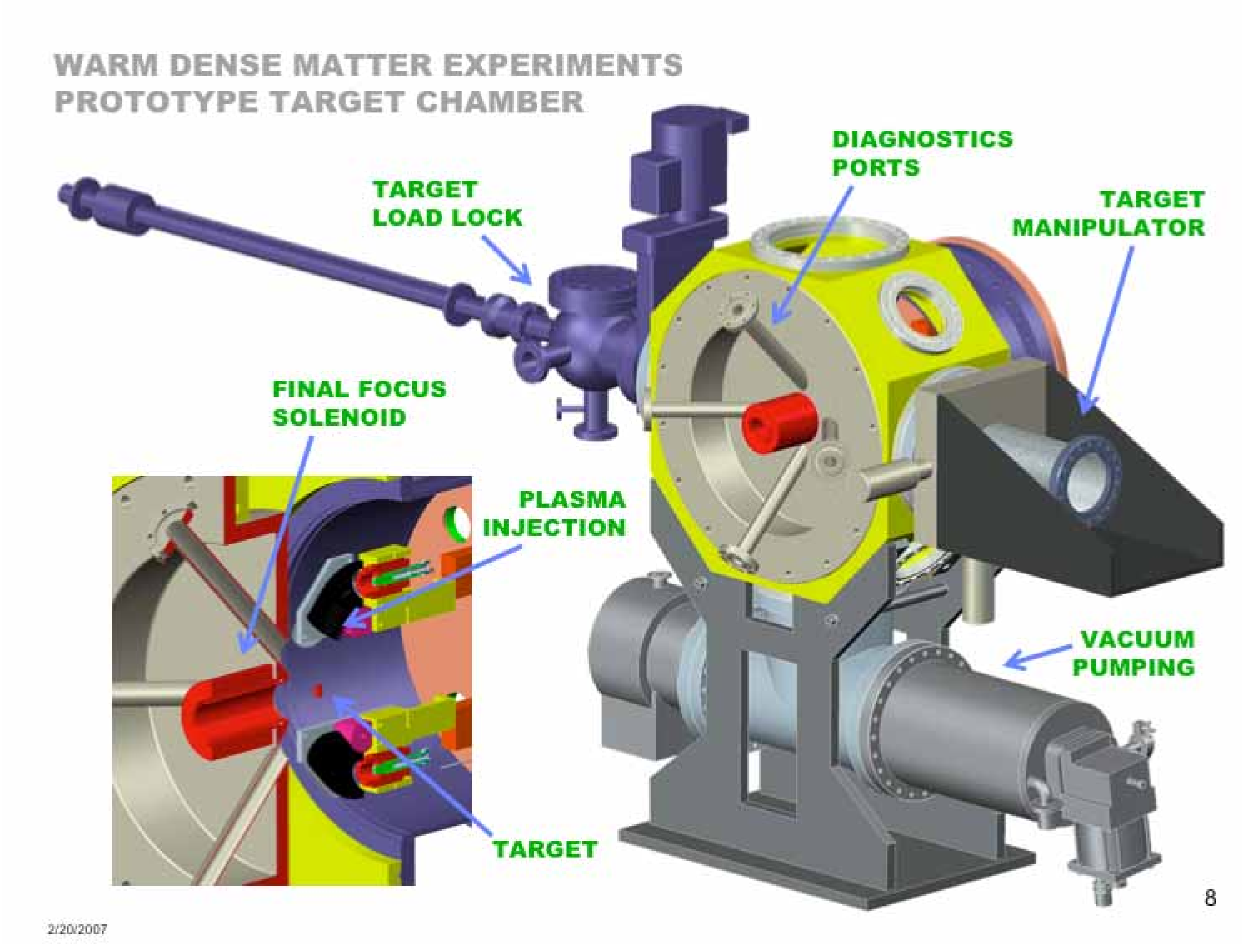
What is the temperature (for each element) above which, there is no distinction between liquid and vapor, and what is the density at this point (i.e. what is the critical point)? What are the material properties (pressure, thermal and electrical conductivity, opacity, viscosity, etc) at this point? As material cools from above the critical point, how fast do droplets form? What happens when ionization occurs at critical point for some materials?

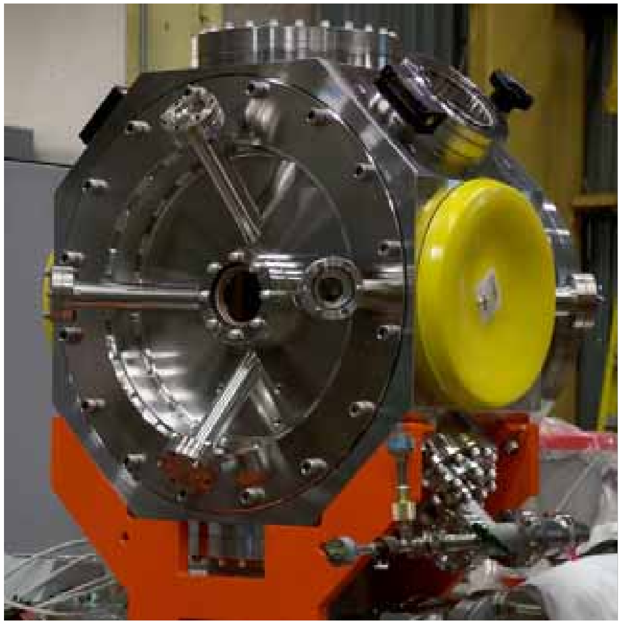


Critical point measurements	>1.0	?	√

time

WDM target chamber is designed and being fabricated



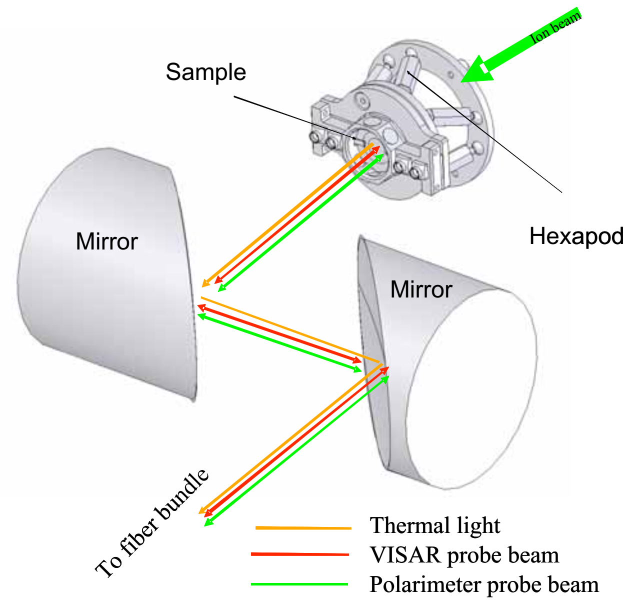


Target chamber as of April 19, 2007

We are developing target diagnostics for first target experiments on NDCX-I (see F. Bieniosek poster)

Fast optical pyrometer

- New design by P. Ni for fast response (~150 ps) and high sensitivity
- Temperature accuracy 5% for T>1000 K
- Spatial resolution about 10 micron at 1 eV
- *Now being assembled*



Fiber-coupled VISAR system – *now under test*

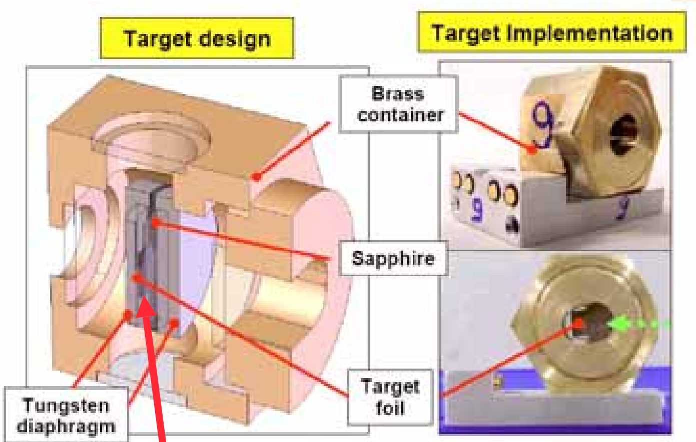
- ps resolution
- 1% accuracy

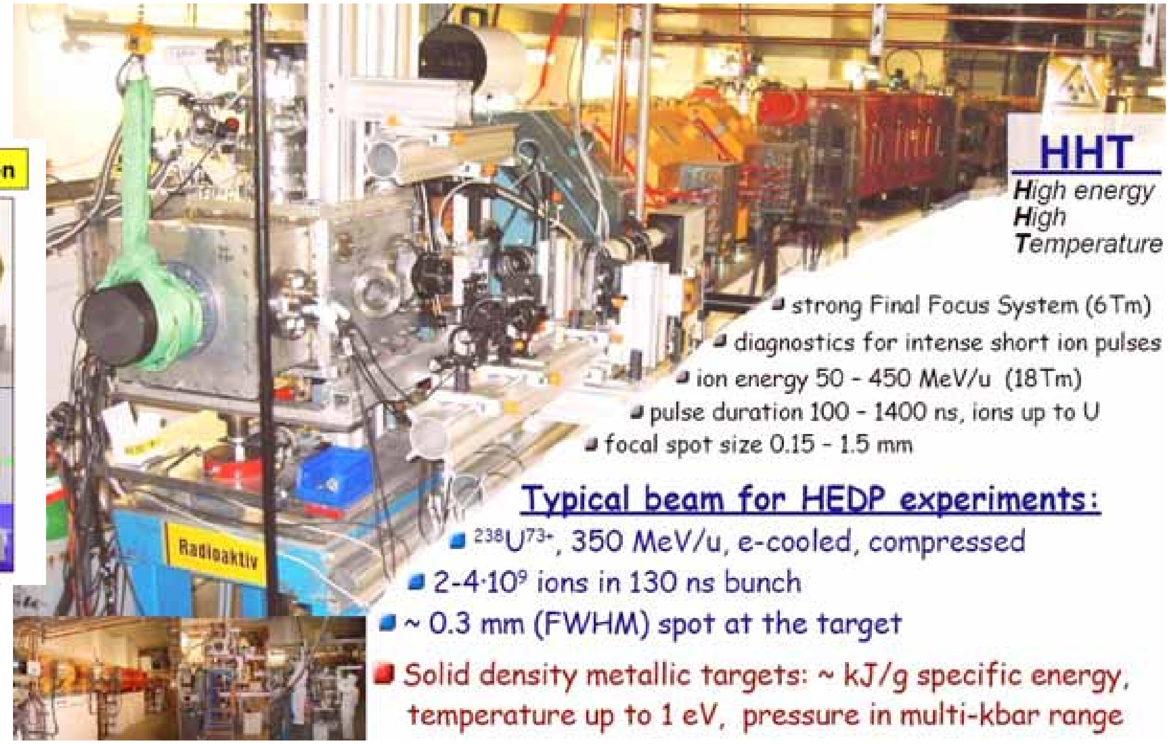
Hamamatsu visible streak camera with image intensifier

- ps resolution
- *arrived Feb. 2007*

All ready by end of summer

VNL porous target experiments at GSI have already begun (see F. Bieniosek's poster for more details)

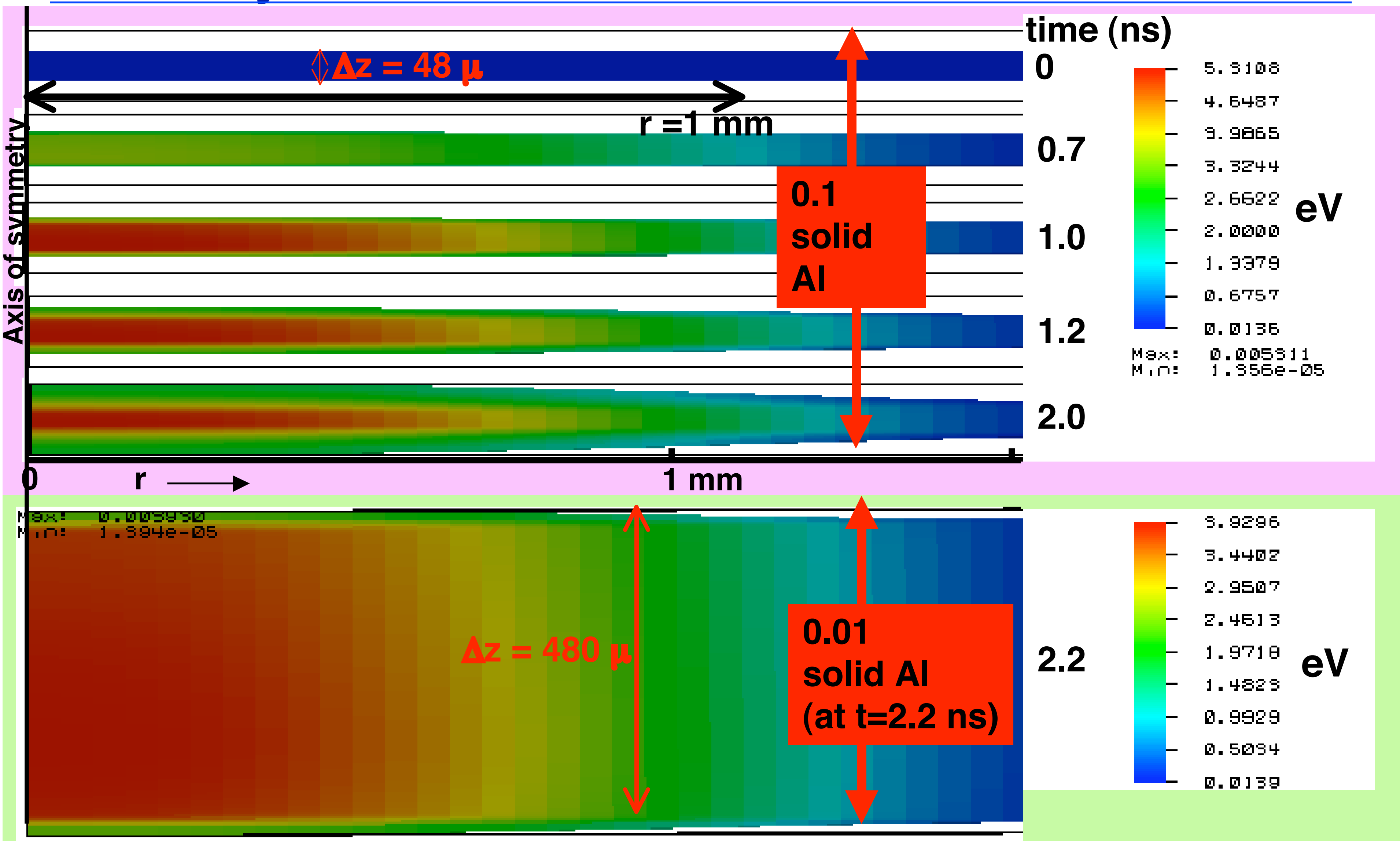




- Replace target foil with porous material.
- Study effect of pore size on target behavior using existing diagnostics.
- Sample targets: LLNL (Au, 50 nm), Mitsubishi (Cu, 50 micron).

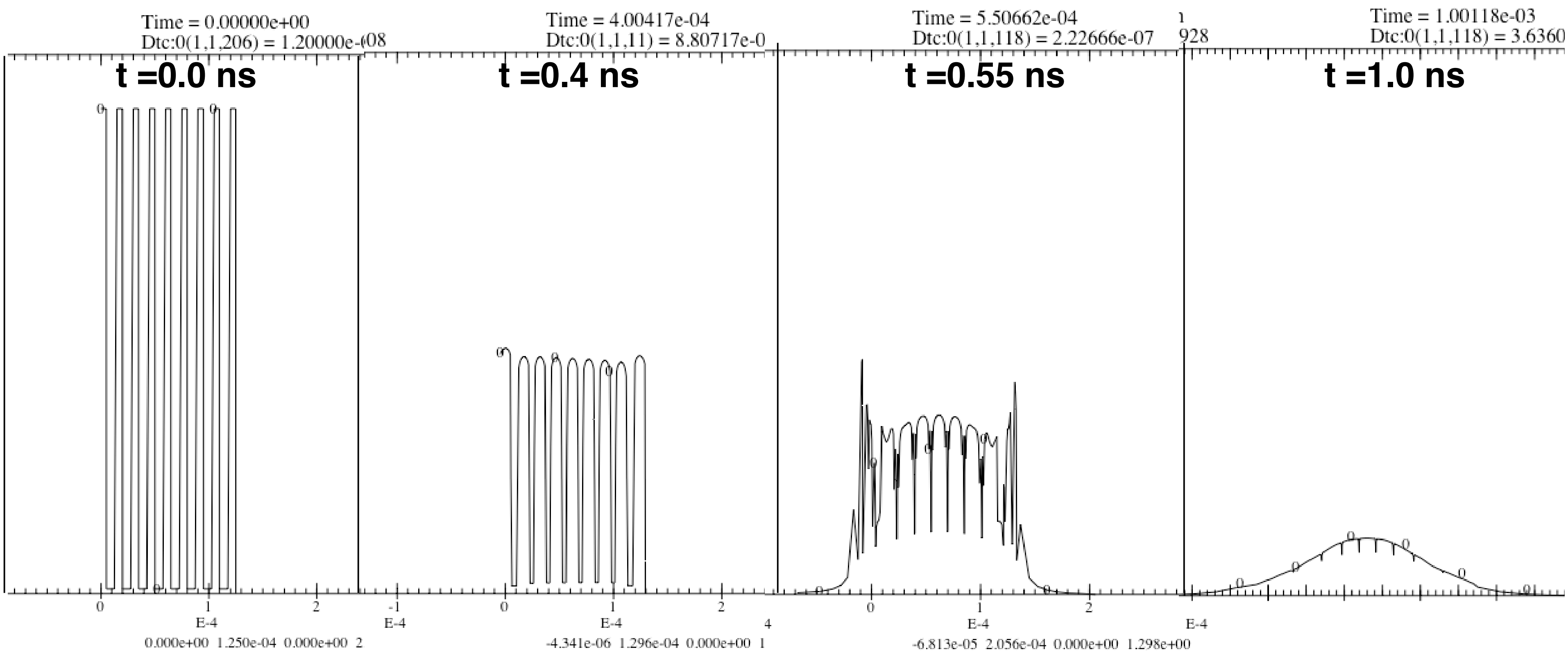
UCRL-PRES-230880

HYDRA beam-heating simulations validate temperature uniformity



(simulations for 0.3 μC, 20 MeV Ne beam -- possible NDCX II / IB HEDPX parameters).

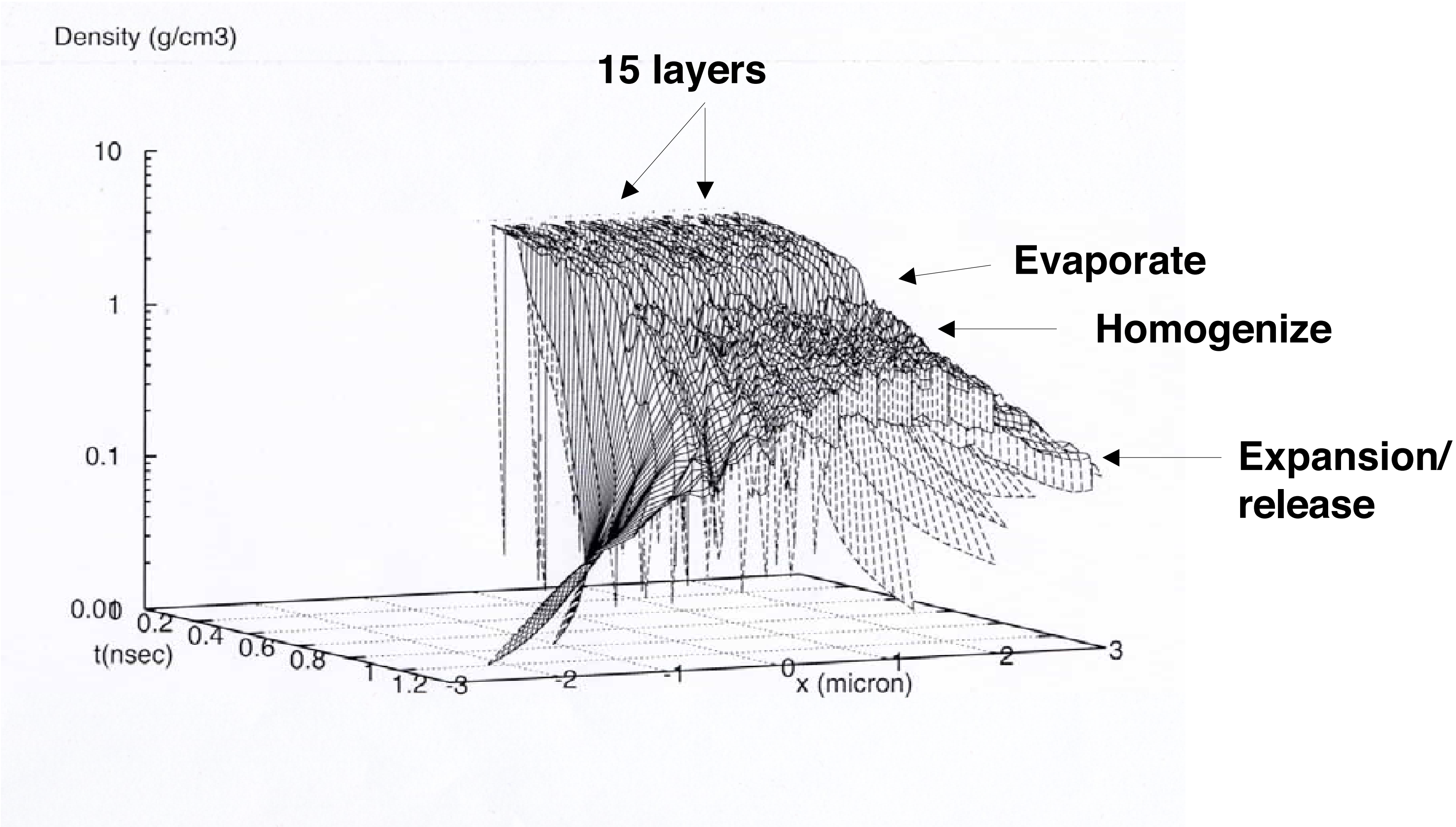
We simulate foams as multiple layers (solid density interspersed with low density voids)



density vs position
average density = 0.33 solid density

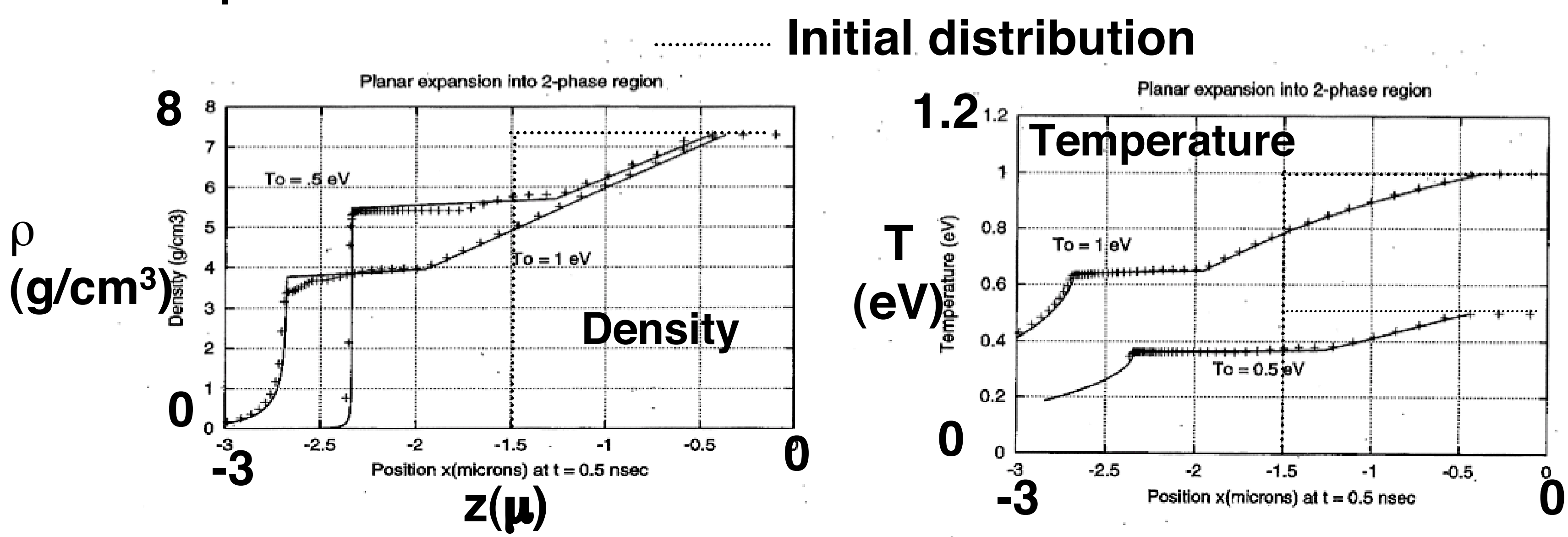
Studies being carried out using both HYDRA and DPC (R. More).

Using DPC with different EOS, qualitatively similar results are obtained



New EOS predicts a sharp density cliff which may facilitate detection and help determine critical points

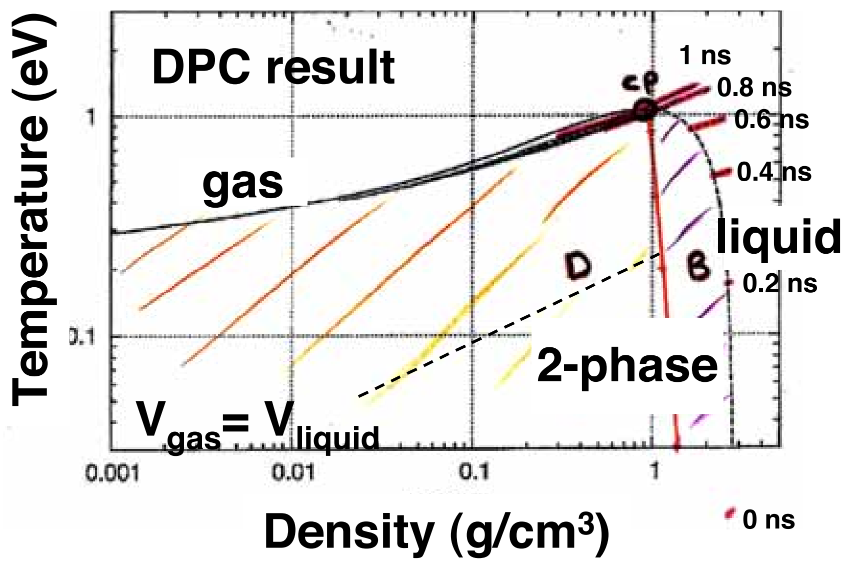
1D hydro calculations using DPC (R. More).
New EOS based on Saha equation with known energy levels (in contrast to QEOS, which uses "average" (Thomas Fermi) atom model)
Two phase medium results in temperature and density plateaus with sharp interfaces



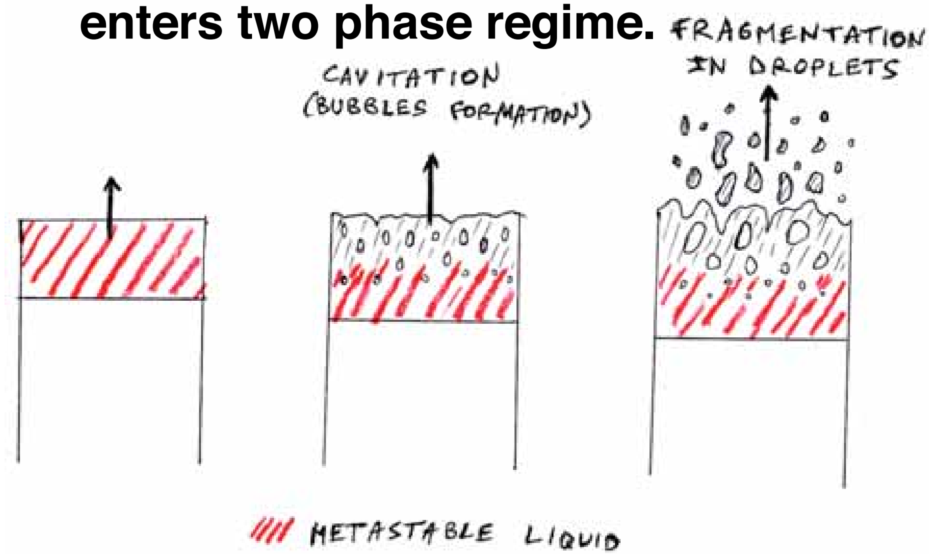
Example, shown here is initialized at T=0.5 or 1.0 eV and shown at 0.5 ns after instantaneous "heating."

Formation of droplets during expansion of foil is being investigated

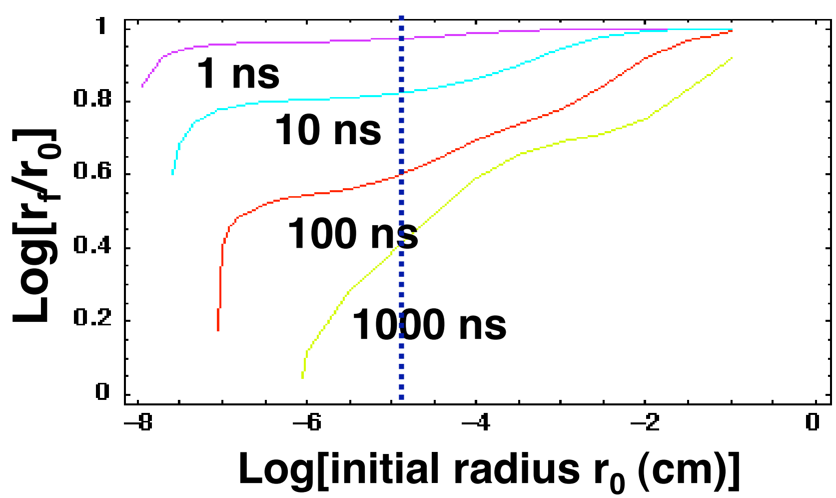
Example of evolution of foil in ρ and T



Foil is first entirely liquid then enters two phase regime.



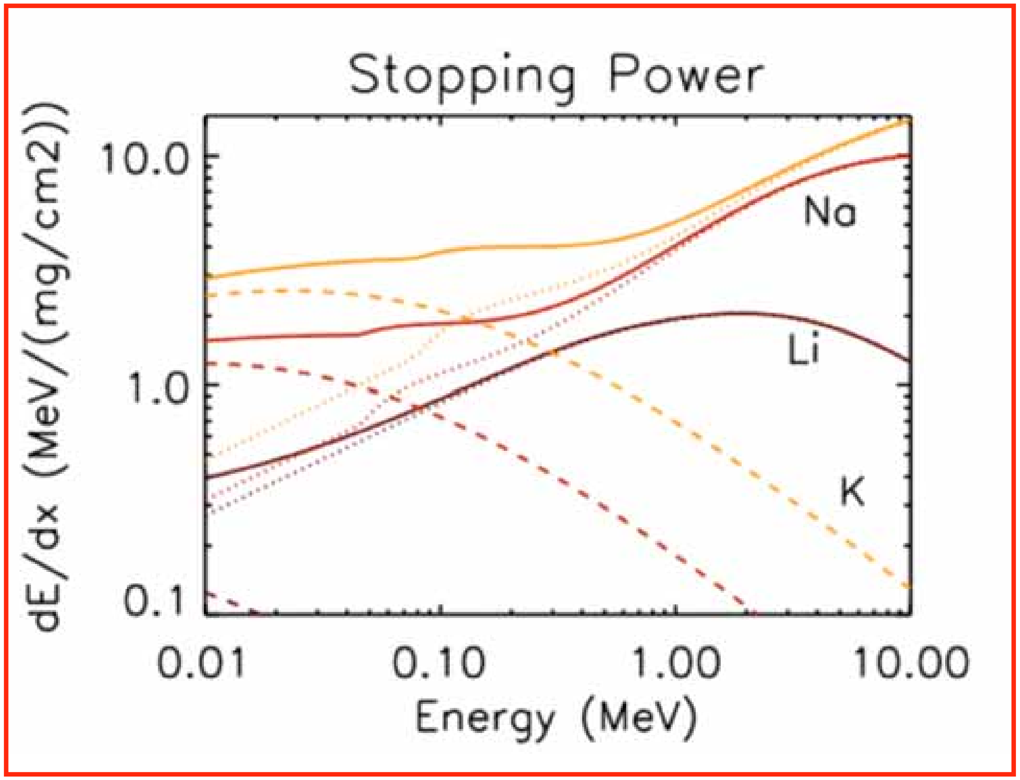
Ref: J. Armijo, master's internship report, ENS, Paris, 2006.



Evolution of droplet radius, (Armijo et al, APS DPP 2006, and in prep).

C. Debonnel and A. Zeballos are incorporating a model for surface effects into hydrodynamics code Tsunami

Extended and improved ion deposition algorithms for low energy ions are being developed for hydro codes



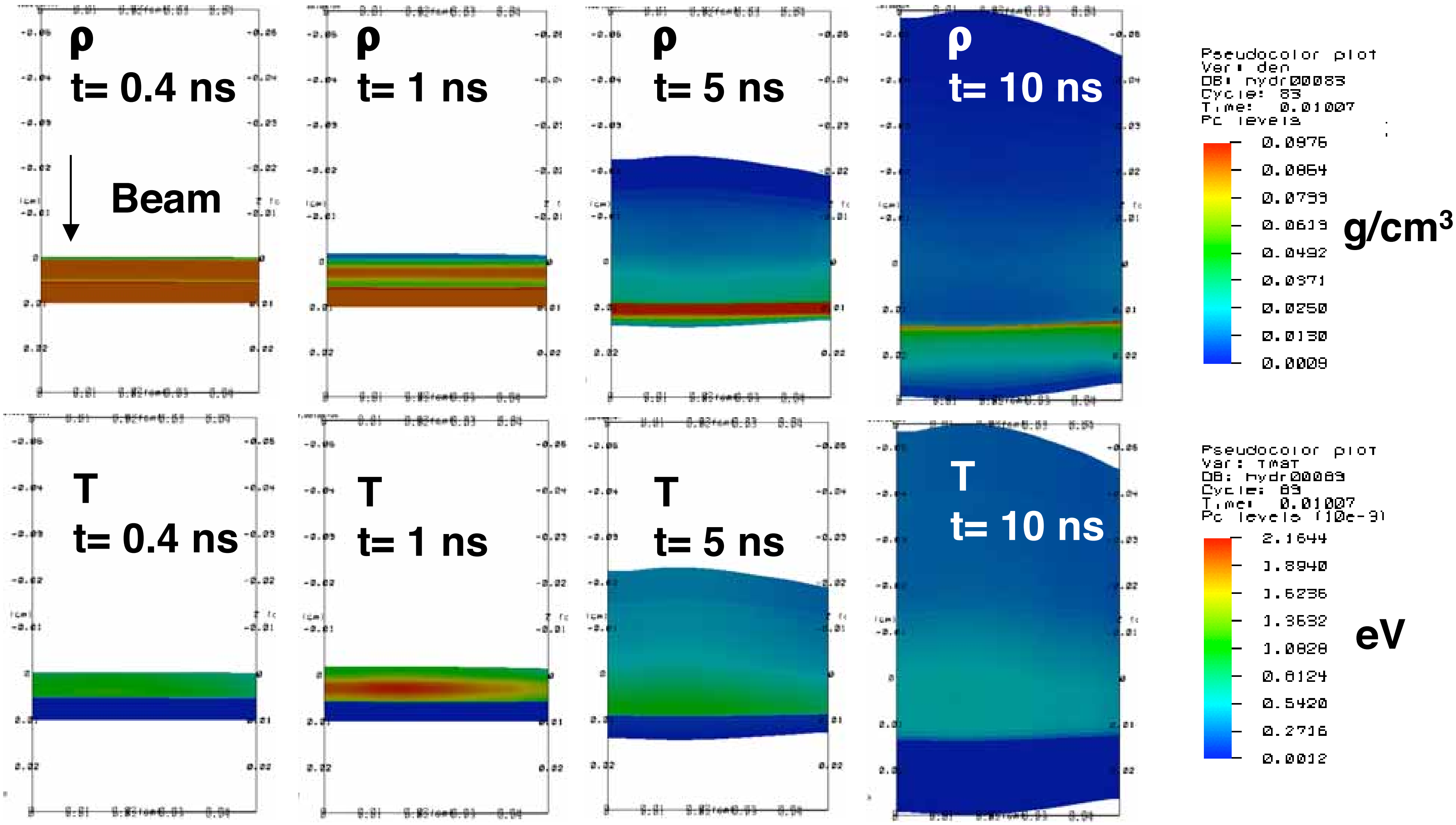
Tech-X Corp. stopping algorithm reproduces SRIM (industry standard code) results in the cold target limit, over a large range of beam energies, but extends results to finite T

Nuclear stopping important at lower energies (eg. 400 keV K^+ beams)

(Tech-X package Txphysics results at left.
Dashed: nuclear stopping;
Dotted: bound electronic;
Solid: total)

S. Veitzer, P. Stoltz (Tech-X) working with M. Marinak (LLNL) to modify HYDRA code.

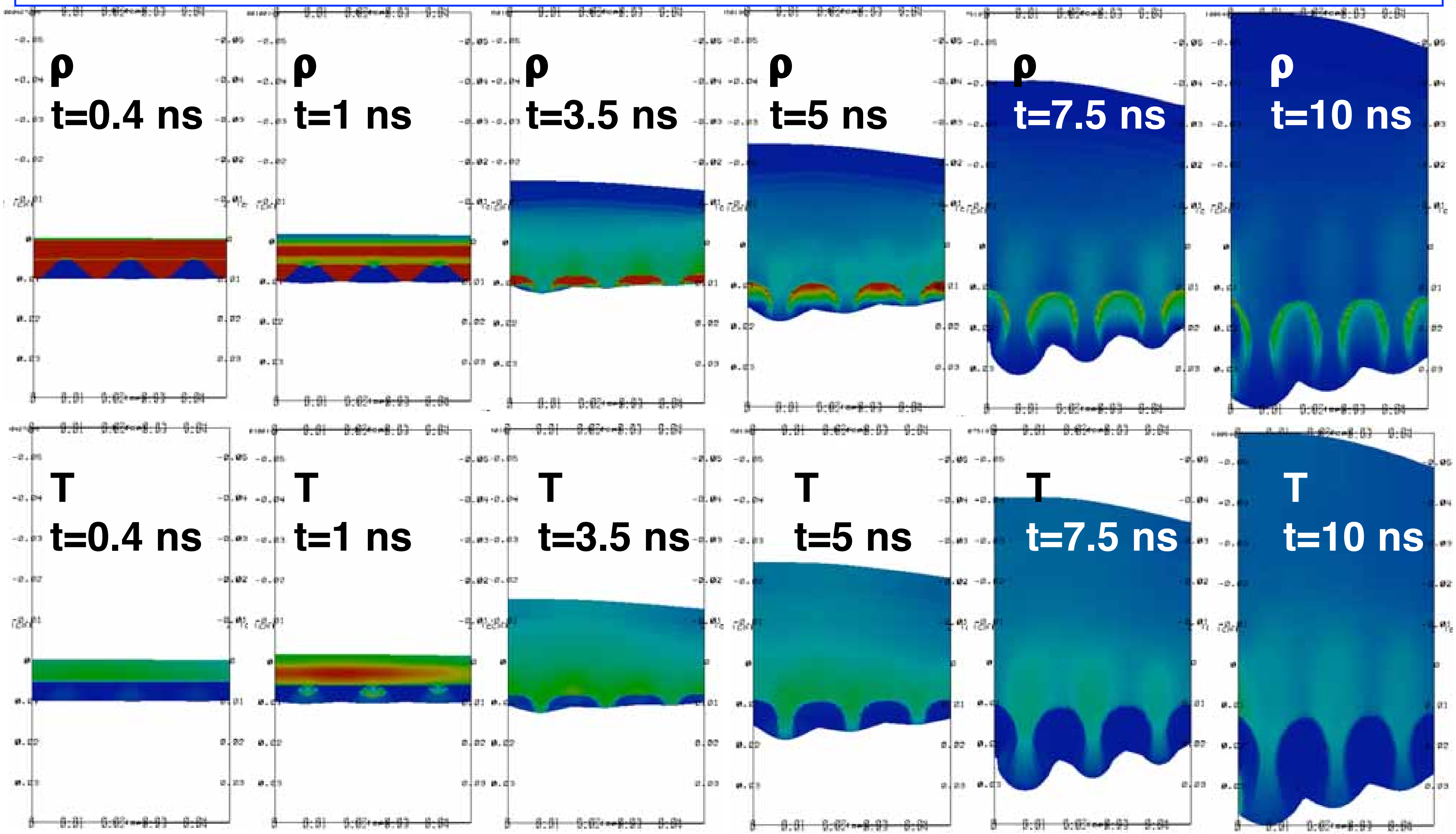
We have begun using Hydra to explore accelerator requirements to study beam driven Rayleigh Taylor instability



23 MeV Ne, 0.1 μC, 1 ns pulse (NDCX II/IB-HEDPX) impinges on 100 μ thick solid H, T=0.0012eV, ρ =0.088 g/cm3; No density ripple on surface, blowoff accelerates slab

UCRL-PRES-230880

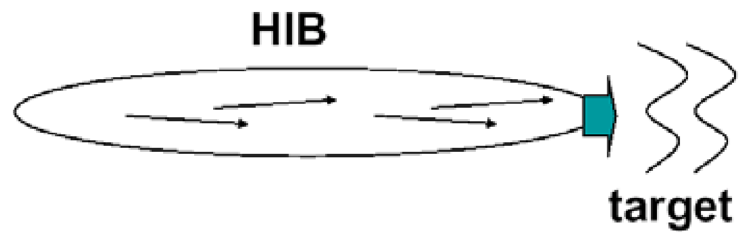
When a density ripple imposed, evidence of Rayleigh Taylor instability is observed in the simulations



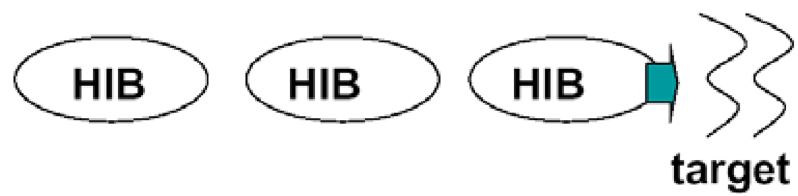
➔How does ion-driven RT differ from laser driven RT?

S. Kawata (Utsunomiya U.) has proposed several techniques to reduce RT growth in ion-beam-driven direct drive

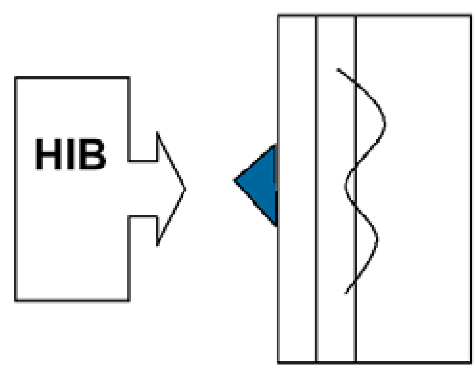
HIB axis rotation or swing
-> reduce the R-T growth!



Successive HIBs induce a dynamically Oscillating *g*!
-> reduce the R-T growth!



Large-scale HIB-energy deposition profile
-> Large-scale density gradient
-> Reduce the R-T growth!



$\delta g(x)$, induced by an shaped Ablator, controls R-T phase & growth

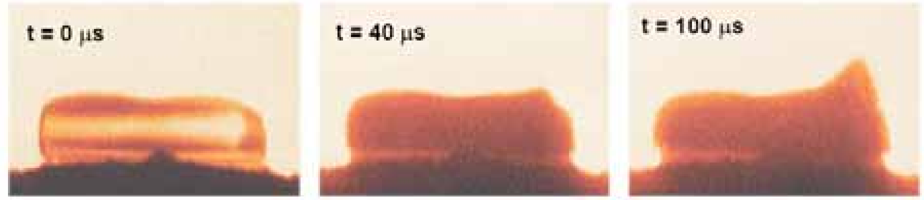
L&PB, 11(1993)757

Shaped target with an Ablator for R-T phase control

→These techniques can be explored on NDCX-II or IB-HEDPX

Ion-driven hydrodynamic studies on cryogenic hydrogen could be carried out on NDCX II or IB-HEDPX scale facilities

- ***GSI first practiced ion-driven target hydrodynamics with cryogenic Xenon targets at beam intensities well below those required for full target ionization:***

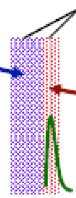


- **Direct drive hydrodynamics/RT physics can benefit from "pump-probe" double pulses:**

Solid D_2 "payload"

Payload and ablator D_2 layers are doped with different impurities to diagnose optical depth modulations

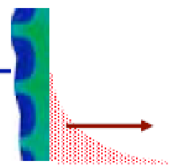
Time just before first pulse



Ablator D_2 layer ~ > than initial ion range

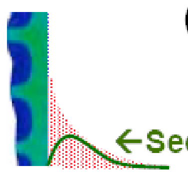
← First ns ion beam pulse dE/dx (beam enters from the right)

Time ~ 10 ns later before second pulse arrives



RT "bubbles & spikes" grow measurable amplitudes.
(1) Can upstream beam GHz RF modulation reduce RT?
(2) Do RT non-uniformities in ablation plasma smooth out with time and distance (any "ablative stabilization")?

Second ion pulse arrives, and stops *<u>mostly within ablation blow-off</u>* (in 1-D approx.)!

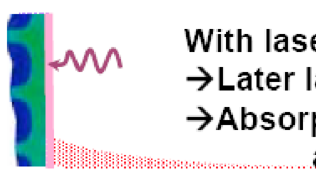


(1) "Rocket science": what ion range/ablator thickness maximizes hydro implosion efficiency with later ion pulses re-pressurizing same ablation layer mass?

←Second ns ion beam pulse dE/dx

(2) How is RT growth affected (any "cloudy day" effect?)

With laser direct drive, later pulse ablates at fresh critical density layer further left



With laser direct drive, ablation plasma << critical density,
→Later laser light transmits through ablation plasma.
→Absorption in inverse bremsstrahlung layer moves left as ablator layer erodes

← Unique physics with ion drive using NDCX-II

The HIFS VNL plan is to create accelerator facilities that are relevant to both WDM and HIF

The physics of ion driven volumetric energy deposition is significantly different than energy deposition by lasers, so that exploring this hydrodynamics will yield new science results, beyond the original WDM mission

Hydrodynamic studies of the acceleration and stability of solid target foils can yield insight into the physics of ion-driven direct drive targets.

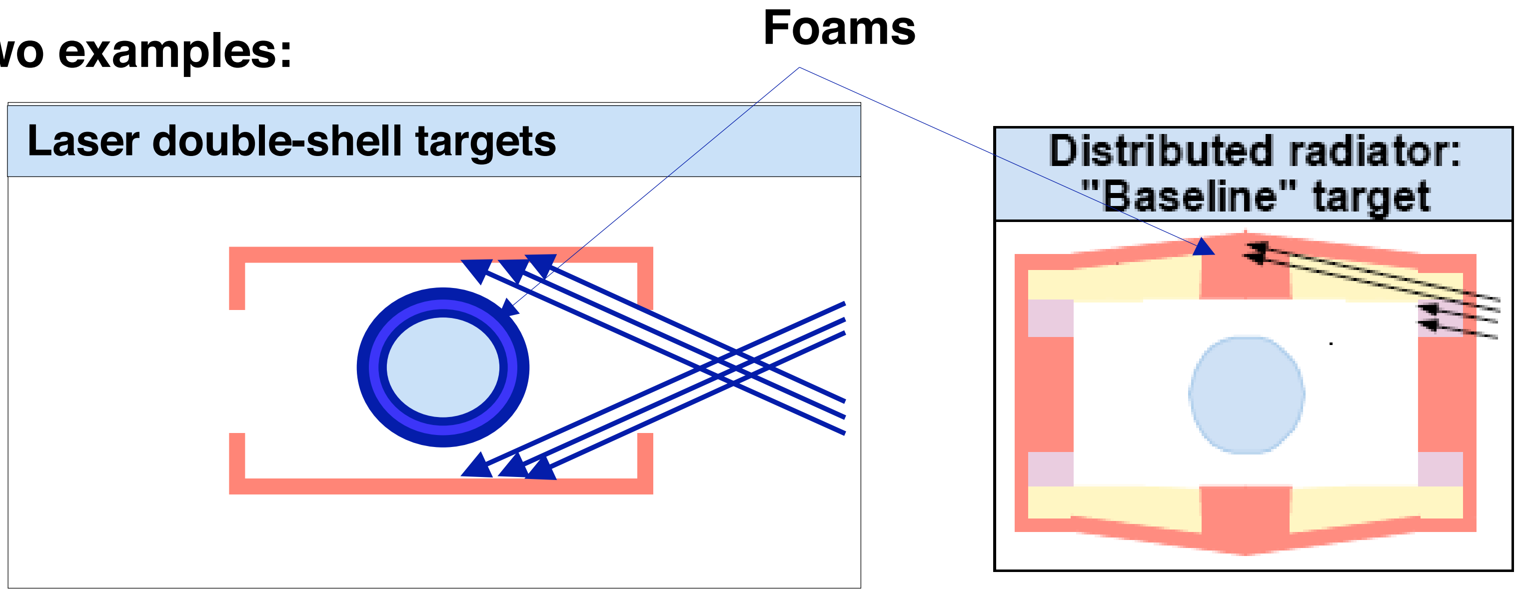
Recent innovations to enable ion-driven HEDP also enable direct drive modular drivers for HIF or target hydro experiments

Minimum pulse energy for studying implosion physics has been estimated by G. Logan to be ~ 10 kJ. Direct drive experiments with such ion beams might supplement NIF laser target data.

WDM and hydro studies have direct impact on IFE

- Effects of preheat
- Early-time hohlraum hydro
- Target debris physics
- Performance of foams

Two examples:



- Ion deposition, acceleration, and stability

Conclusion

Heavy Ion Fusion Science experiments on NDCX I are making outstanding progress in neutralized compression.

Warm Dense Matter experiments are beginning

-- Transient darkening experiments on HCX

-- Metallic foam studies at GSI

-- Target heating experiments (~.2 - .5 eV) to begin this year on NDCX I

-- 1 eV experiments on NDCX II by 2009 (assuming 1.5 M$ funding increase)

Hydrodynamics experiments for stability and ion physics deposition studies can be carried out on NDCX II and/or IB-HEDPX. Simulations being carried out.

Magneto-Inertial Fusion:

A pathway to Magnetized HEDLP

Glen A. Wurden

IFE Strategy Planning Workshop

April 25, 2007

Abstract

The category of magnetized high energy density laboratory plasma (MHEDLP) provides a way to achieve keV temperatures and Megabar pressures in a (relatively) large volume of compressed HED plasma. Magneto-inertial fusion (MIF) combines aspects of magnetic and inertial confinement to achieve high density fusion relevant plasmas in ultra-high magnetic fields. In particular, at scales where both the thermal electron and ion gyroradii are smaller than the plasma size, and even the fast alpha gyroradius is small. Yet the densities are high, so that we have a situation requiring kinetic simulations (high collisionality, even at fusing conditions) and radiation coupling in addition to hydrodynamic models at boundaries. Compression dynamics can be slow and adiabatic, or fast with shocks, or perhaps even both. Progress is being made with two approaches to achieving MHEDLP. These are: compression of a seed magnetic field frozen into a plasma driven by solid liners, or by plasma liners. The particular drivers use pulsed power or explosives (both driving MA currents), and lasers. A LANL/AFRL experiment using a field reversed configuration (FRC) target will be testing MIF to MHEDLP conditions, with integrated plasma/liner implosions being conducted at the 1.5 MJ level in FY2008. Experiments at OMEGA are compressing seed magnetic fields with shells driven by lasers. Technology development of drivers with guns to produce multiple converging plasma jets are also in progress.

Dense Plasmas in Ultrahigh Magnetic Fields

Overarching Question: Can fusion-relevant thermonuclear temperatures be obtained when plasma is compressed with megagauss fields?

- Recently we (~30 contributors) wrote a community white paper on Magnetized HEDLP. (April 20, 2007)
- Copies will be available at

http://fusionenergy.lanl.gov/mhedlp-wp.pdf

- Merging OFES panel recommendations with Davidson reports
- Basically, adding a new research thrust: dense plasmas in ultrahigh magnetic fields, or MHEDLP

Science issues:

Can multi-keV temperatures be obtained by compression of a magnetically confined plasma to megabar pressures using a solid metal liner?

- *What limits liner compression and dwell time? How do nearby boundaries (walls) driven by intense magnetic and radiation fields turn into plasmas? How are hydrodynamic instabilities at boundaries changed in the presence of a thermonuclear (fusing) plasma? How can we minimize impurity influx?*
- *Do we have the right material conductivity and transport models (for both walls and plasma)? What effects do velocity shear, initial density profile, finite Larmor radius, and other conditions have on particle and energy transport at MHEDLP conditions?*
- *Can we take advantage of ultra high magnetic fields and high density to enable plasma diagnostics that are not possible in more conventional regimes?*

Solid liner/plasma science questions (continued)

- *What happens when the liner stagnates on the plasma target pressure? What is the realistic energy partition between liner ablation consequent generated plasma, radiation and ion flux? How does the sheath at the liner- plasma boundary behave? To what extent do the liner and plasma mix?*

- *How can we scale the coexisting high magnetic fields in HED laboratory plasmas to situations of interest? For example atomic physics changes greatly when the ambient magnetic field is much larger than that inside the electron orbitals. White dwarf stars have similar high fields and density.*

- *Do the FRC scaling laws hold as expected for strong boundary compression? Can strong elongation increase MTF fusion yield? Can an elongated liner remain stable as it is compressed?*

MHEDLP science issues (continued)

- *How can plasma be formed, accelerated and focused to form dense, high Mach number, high velocity plasma jets and/or plasma liner suitable for compressing a magnetized plasma to thermonuclear temperatures and for magnetized HEDLP research?*
  - *Do instabilities in the compression of a magnetized plasma by a plasma liner behave as predicted and how can they be controlled?*
  - *What are the transport properties of magnetized plasma during compression? Could magnetic fluctuations or other instabilities be excited by the compression? How do the magnetic flux and field lines behave during the compression?*

- *What is the highest magnetic field that we can produce terrestrially?*
  - *What new multi-body, atomic, and quantum effects can be understood in the regime which combines HEDP with ultra-high magnetic fields?*

What is Magnetized Target Fusion (MTF)?

- The difference between Magneto-Inertial Fusion and Magnetized Target Fusion? MIF is a superset of MTF. Not all MIF scenarios begin with a magnetized target plasma. Magneto-inertial fusion (MIF): uses inertial particle confinement and magnetic thermal insulation
- Magnetized Target Fusion (MTF): uses inertial compressional heating and magnetic thermal insulation, starting with a plasma with “frozen” magnetic fields
  - A way to heat and compress a starting (target) plasma to high temperature, density, and magnetic field, resulting in significant fusion gain
  - Operates at ~ 1 Megabar pressure (or higher).
  - A Magnetized High Energy Density Laboratory Plasma (MHEDLP) approach to pulsed fusion.
- MTF-FRC: uses inertial compression to attain high B, with both magnetic thermal and magnetic particle confinement (ie, closed field lines). Plasma beta remains near unity, during entire process.

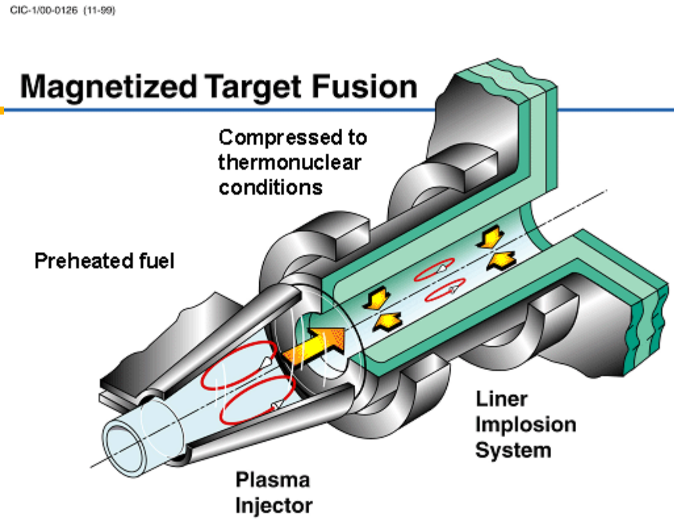
MIF/MTF approach has many common features with IFE

- Pulsed, rep-rated systems, storage and switching of driver energy
- Achieving driver stand-off under rep-rated conditions (but the problem typically takes a different form)
- Designing a chamber to take the intense energy and particle loads
- Chamber clearing
- Isotope and chemical separations at the back end for DT and blanket materials

<u>There are also some significant differences:</u>

•Target physics/gain
•Target manufacture/formation
•Electrical connections
•Symmetry needs
•Driver power levels

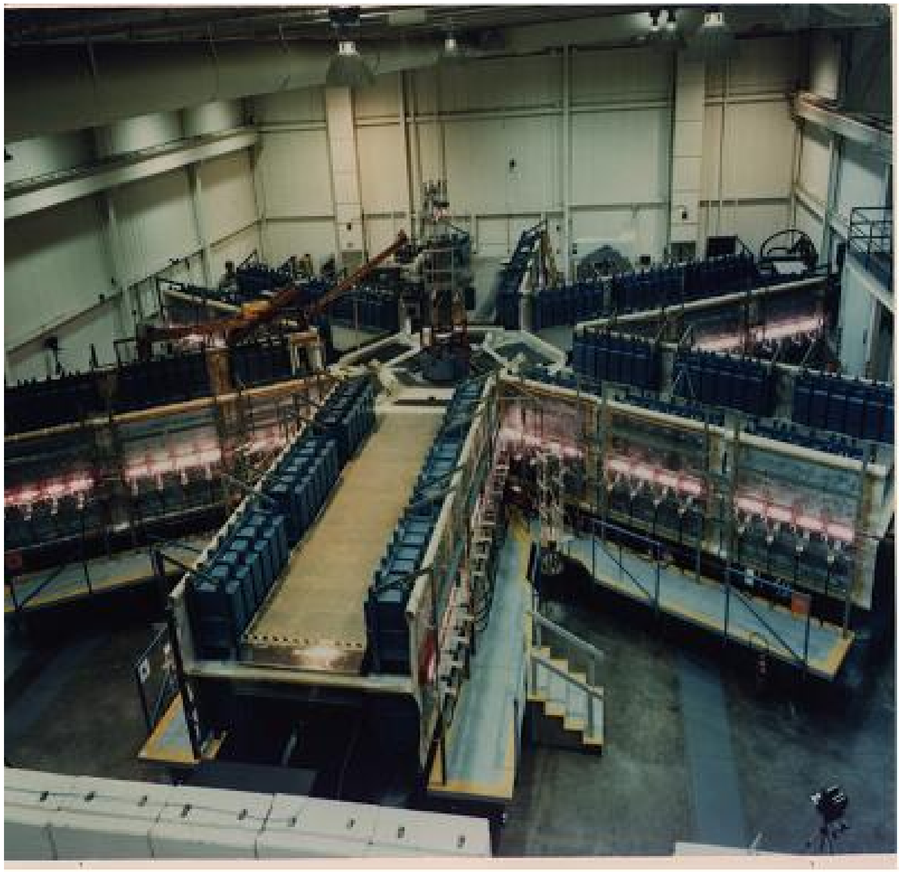
Magnetized Target Fusion (FRC):



This is a fusion concept where:

- The plasma beta ranges from 0.8 to 1
- The heart of the device fits on a modest table-top
- The plasma density is intermediate ~10^{19} cm^{-3} (MFE~10^{14} cm^{-3}, ICF ~10^{25} cm^{-3})
- The current density can be 1000 MA/m^2
- The magnetic field confining the plasma is 500 Tesla
- The auxiliary heating power level is ~ 1000 Gigawatts
- MHEDP achieved by "slow" adiabatic compression (to ~1 MBar)
- Research can be conducted with existing facilities and technologies
- In a reactor, on each pulse the liquid first wall is fresh➔ no materials problem!
- The repetition rate would be ~0.1 Hertz, so that there is time to clear the chamber from the previous event

(DOD) Shiva Star Facility at AFRL



Parameters for magnetic pressure implosions of cylindrical or spherical metal shells (solid liners)

- 80 to 90 kV, 1300 uF, 25 to 45 nH

- 11 to 16 Megamp, ~10 μsec risetime discharge implodes 10 cm diameter, 1 mm thick, 4 to 30 cm long Al liner in 15 to 24 μsec

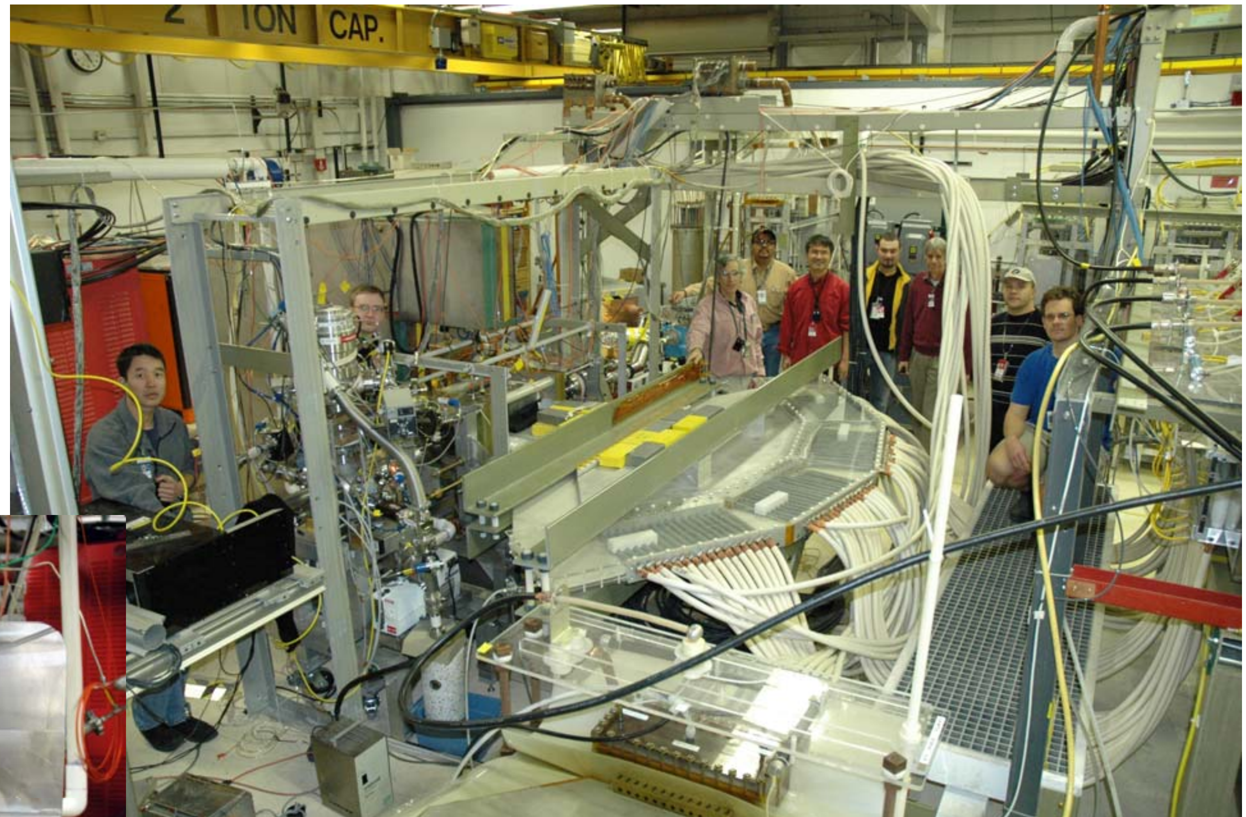
- e.g., 4.4 MJ energy storage gives 1.5 MJ in liner KE

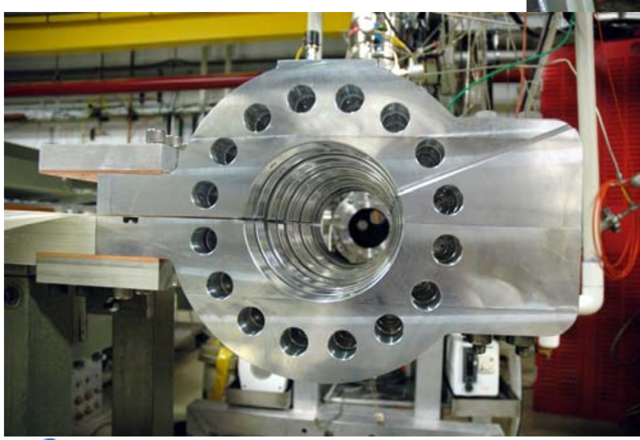
Shiva Star Capacitor Bank (up to 9 Megajoules, 3 μsec) used for implosion - compression experiments

LANL's FRX-L Field Reversed Configuration (FRC) for MTF target plasma development

Project/Concept Description: Develop a suitable plasma injector using a high density FRC

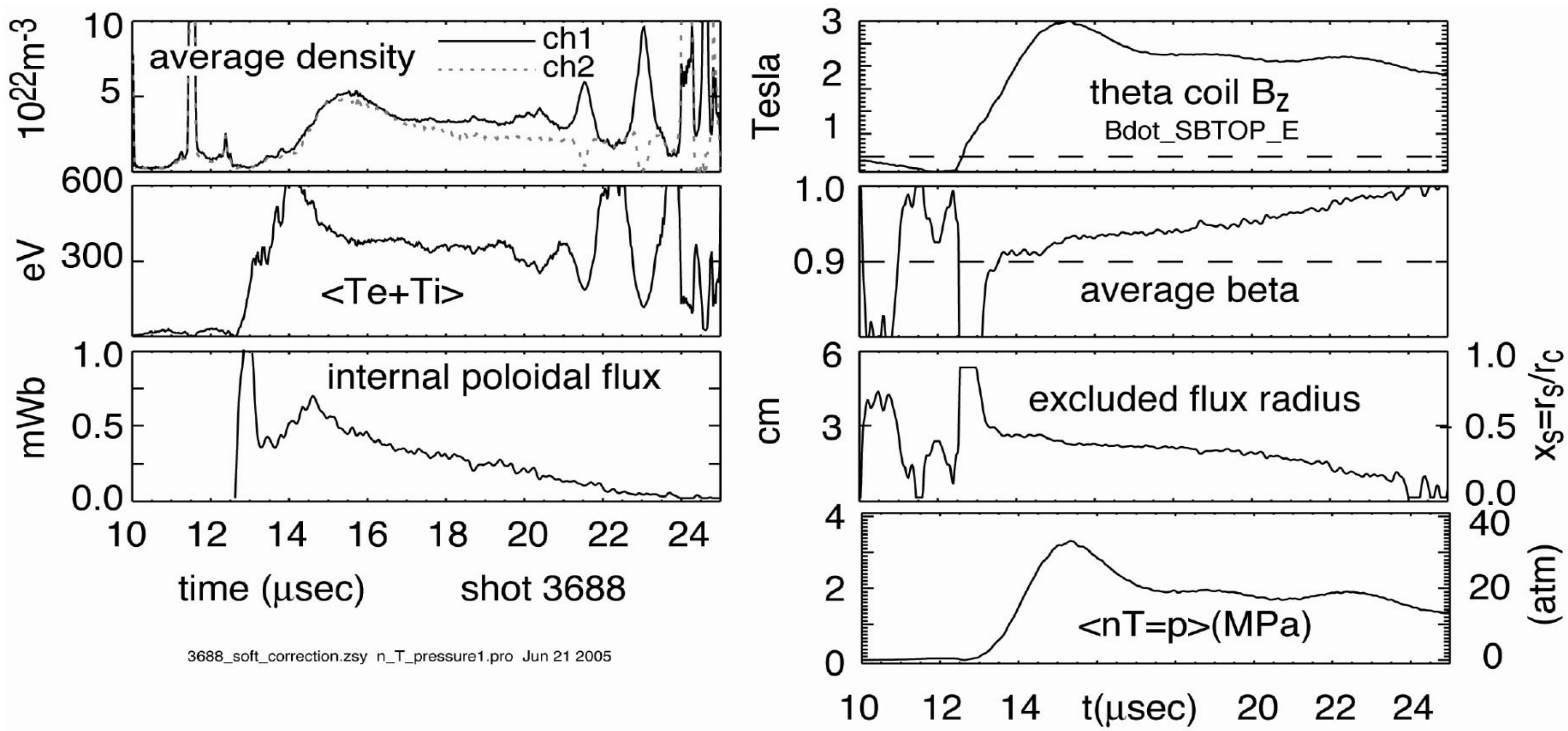
GOAL: To make the first physics demonstration of MTF by imploding an FRC plasma with a metal liner, in FY2008





- The FRX-L experiment and team

High pressure FRC plasmas are produced in FRX-L



FRC parameters in FRX-L, following installation of improved high-current crowbar system. The plasma pressure is 2-3 MegaPascals, (20-30 bars); higher than even the highest field tokamak plasmas. An n=2 rotational instability develops by t=20 µsec, terminating the plasma.

LANL/AFRL Magnetized Target Fusion physics compression of FRC in FY2008

- We will conduct a series of shots on Shiva Star (a DOD facility) testing wall conditions, perturbations, while measuring DD & Triton burn-up fractions
- Cost estimate $130k-150k per incremental shot, depending on which parts survive
- We will continue to improve FRC translation physics & increase modeling efforts

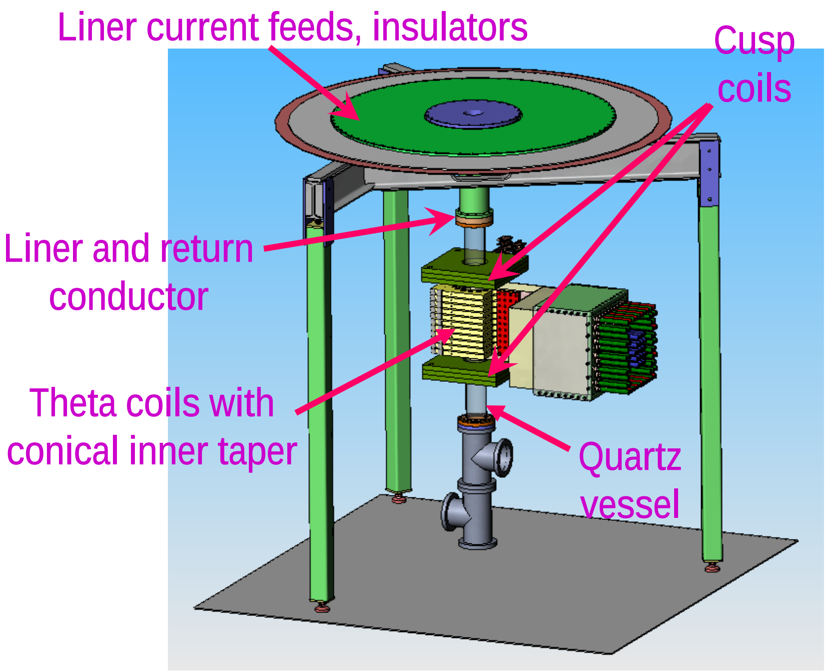
2 postdocs, 1 grad student, 5 undergrads

- FY07: started FRC experiments at AFRL; preparing integrated FRC formation – translation – liner compressional heating experiments; improved simulations, modeling FRC spin-up and rotation behavior under compression

- FY08: FRC formation – translation – liner compressional heating experiments

- FY09: add multipole field stabilization of n=2 instability and/or radial electric field maintenance for counter-torsion of the rotation which causes it

FRCHX at Shiva Star



Energy? Basic points to consider (1)

3.6 MJoules = 1 kW-Hour

10 cents/kWH means 1 GigaJoule of electricity is worth $27.8

At 35% conversion efficiency, then 4.1 GJ thermal is worth only $40 of electricity

One metric ton (1000 kg) of high explosive has an energy content of 4.1 GJ

To produce 4.1 GJ from DT fusion, at 17.6 MeV per DT reaction, and 1 eV = 1.6×10^{-19} Joules, one has 2.8×10^{-12} Joules per DT reaction; so you need 1.4×10^{21} reactions per 4.1 GJ released.

Basic points (continued) (2)

A mole of D2 is $2 \times 6.02 \times 10^{23}$ D atoms, and same for mole of T2. So each 4.1 GJ pulse burns up approximately 1 milliMole of D2, and 1 milliMole of T2. D2 has a molecular weight of 4 grams/Mole, and T2 has a molecular weight of 6 grams/mole

If the fractional burn-up of DT is 10%, then you need 10 milliMoles of each, in the final compressed MTF plasma. At least 20 milliMoles of each in the beginning target plasma, assuming 50% plasma inventory losses during translation from the formation region.

The initial target fuel load must be “preheated” to 200 eV (Te+Ti). This is an energy investment of $2 \times (20 \times 10^{-3}) \times 6 \times 10^{23} \times 200$ eV $= 4.8 \times 10^{24}$ eV, or 0.75×10^{6} Joules, or 0.75 MJ. Add in a factor of 2x for formation losses, so we are talking 1.5 MJ of energy needed to form the MTF “target” plasma.

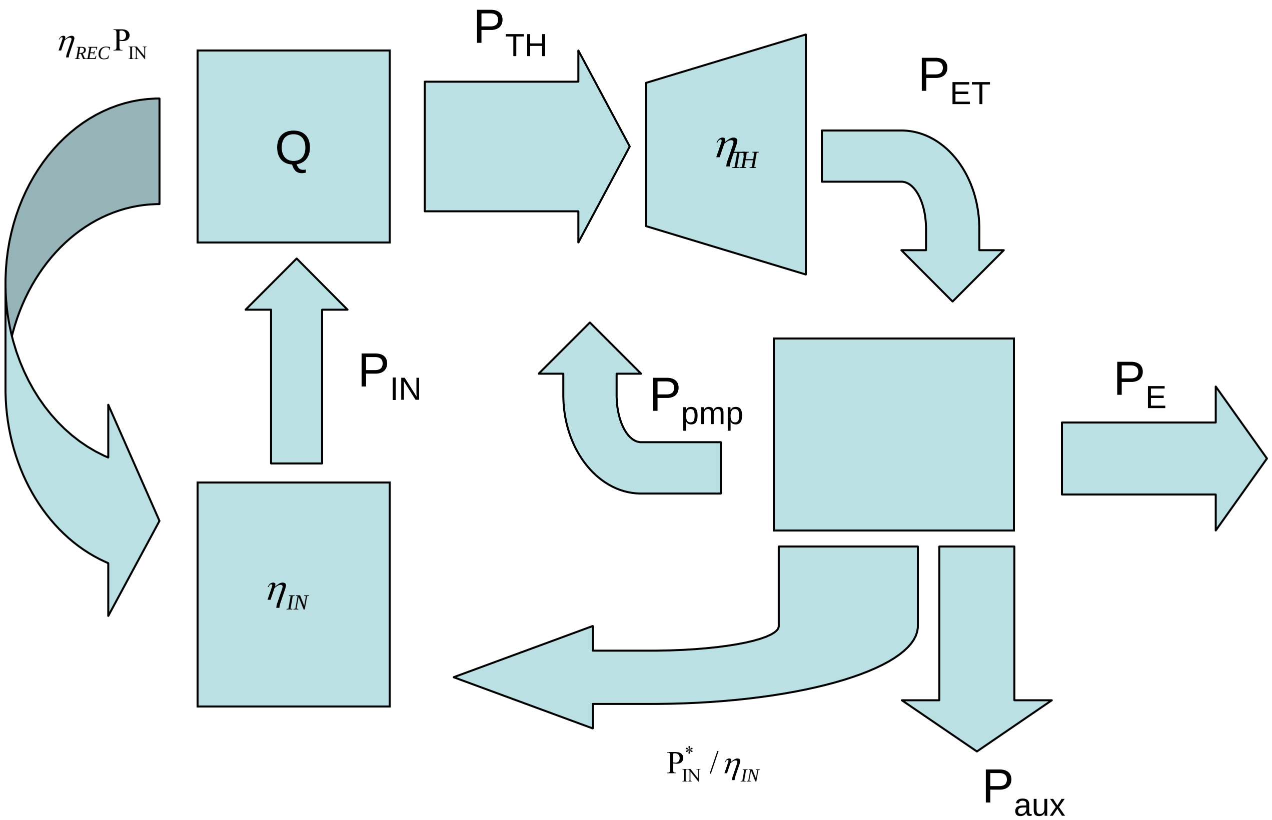
Basic points (continued) (3)

Then the gain is 4100 / 1.5 = 2733 relative to the initial plasma energy content. But work also had to be done to compress the initial plasma to get it to the final state (alphas assumed not to contribute). The energy content of the final state is defined to be same number of particles, heated up to 8 keV. The temperature increase (energy content increase) is 8000/200 = 40. Assume the liner drive energy is about 4x the final plasma state energy. Then the system I have just described only has a gain (classic Q_{DT})~ 17.

If the electric-to-liner drive efficiency is ~50%, the system gain is reduced to ~8, when considered from wall plug to thermal output. (i.e., you needed to put in 510 MJ into the pulsed energy storage to get 4.1 GJ thermal out from pure fusion). If conversion to electricity is 35% efficient, then electricity output is 1.4 GJ, so the recirculating power is about 36% . If the rep-rate is 0.1 Hz, the average electric output is 140 MW.

So a 10% fractional burn-up is just marginal performance, from a fusion-only, MTF batch-burn system.

Where does the power flow? (4)



Power flow chart definitions, to find a required Q as a function of recirculating power fraction ε (5)

M_n = 14-MeV neutron energy multiplication

f_{aux} = auxiliary power fraction

f_{pmp} = primary coolant pumping power fraction

η_{pmp} = primary coolant pump efficiency

η_{TH} = thermal conversion efficiency

η_{IN} = input power efficiency

η_{REC} = recovery power efficiency

Q = DT fusion gain

ε = recirculating power fraction

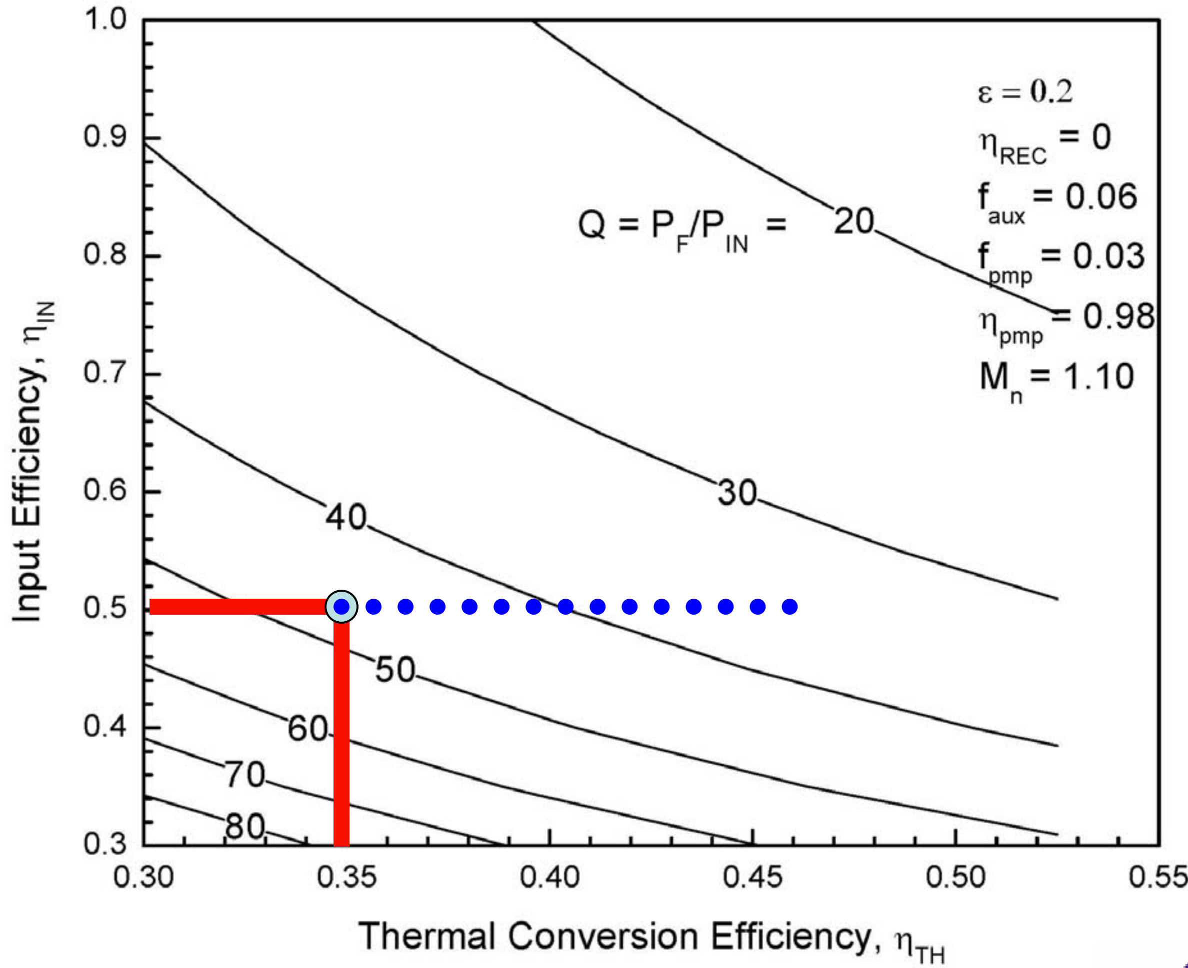
$$P_E = (1-\varepsilon)P_{ET}$$

$$Q = \frac{1}{[0.2+0.8M_n]}\left\{\frac{[1/\eta_{TH} - f_{pmp}\eta_{pmp}][1/\eta_{IN} - \eta_{REC}]}{[\varepsilon - f_{aux} - f_{pmp}\eta_{pmp}]} - (1-\eta_{REC})\right\}$$

The accompanying power flow diagram on the previous page is similar to Fig. IV-2 on pg. 86 of LA-6707-P (1977), which has f_{aux} = 0 and f_{pmp} = 0. Q is DT P_F/P_{IN}, corrected for M_n enhancement. Pending a gain curve [$Q = f(P_{IN})$], all power terms cancel and Q is a function of the target value of ε and the various efficiencies for any/all powers. If some input power can be directly recovered, the value of Q can be reduced.

(provided by R. A. Miller)

To have only 20% recirculating power, with 50% wall-plug-to-plasma heating efficiency, 35% thermal-to-electric, and some credit from exothermic n-Li reaction, you still need Q ~45 **(6)**



Can the neutron energy multiplier be bigger than 1.1?

•Why is it 1.1 for “pure” fusion?….because we take an exothermic energy credit for n-Li reactions in a blanket.

•Are there other possibilites? Yes……..**Fusion-Fission Hybrid, because per fusion, fusion is energy rich, and neutron poor. Fission is neutron rich, and energy poor.**

•If the blanket is 0.6 meter thick hot liquid FLIBE with 10% UF4, one can protect standard solid structural elements for a long life (~30 years), while getting a tritium breeding ratio of >1.1, and an energy amplification of 1.9 (due to fission in the blanket!). [Mustafa Ubeyli, Journal of Fusion Energy, Vol. 25, no. 1-2, pg 67-72, (2006)]

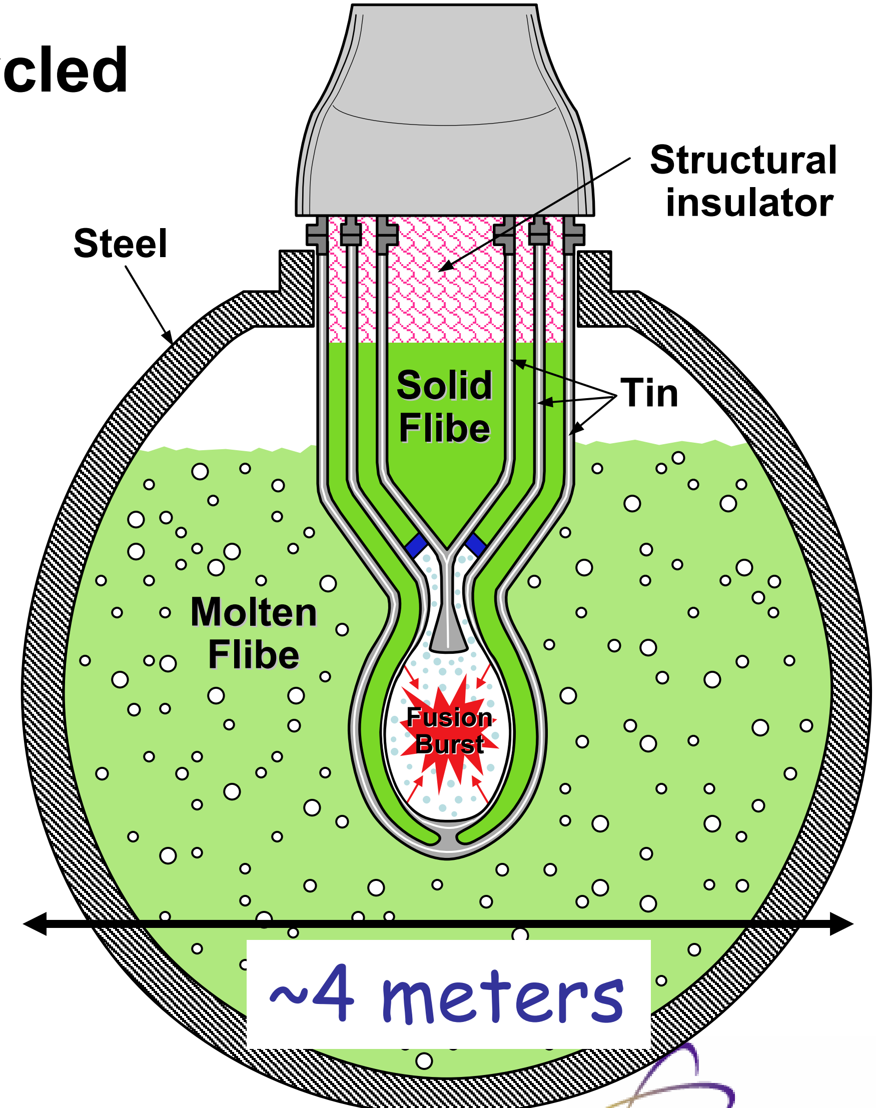
•So, as most of us know, if you are willing to be a fissile breeder, then it is easy to double the Q.

Starting from the End Point

- Consider a 4.1 GigaJoule yield (1 metric ton) from a pulsed MTF device, in a ~1 microsecond burn.
- Consider a rep-rate of 0.1 Herz, which also gives more time to clear the chamber.
- Pick a thermal conversion efficiency to electricity of 35%, so one would produce 1.4 GJ electric per pulse (gross, not net), or 140 MW electricity (average).
- Use a thick liquid wall, with liquid pool at the bottom of the chamber. The liquid will absorb neutrons, and breed tritium. Have voids in it to dissipate shock from the explosion, and cushion the final wall of the system.

One vision of an MTF reactor, with miscible materials

- **All target material recycled**
- **15 sec per pulse**
- **Flibe primary coolant at 550 °C (T_{melt} = 459 °C)**
- **Tin T_{melt} = 232 °C**
- **P. Peterson, UC Berkeley, ~1998**



NNSA

Los Alamos

Differences & similarities between MTF and Z-IFE reactors

•Both envision reactors with multi-GJ yields, and liquid first walls

•Both envision slower rep rates (~0.1 Hz) than IFE, with resultant advantages in clearing the chamber and setting up the target

•Both require target standoff delivery of energy to the imploder (liner/wire array)

•Neither requires target tracking in the reactor chamber

•Z-IFE expects higher Q (due to burning cold-fuel) than batch-burn MTF

•MTF delivers energy on slower timescales, with lower driver voltages, than Z-IFE

•MTF compression ratios and implosion velocities are smaller than needed by Z-IFE

•MTF needs a higher quality vacuum (for its target plasma) than Z-IFE

•It may be possible to combine magnetic insulation with a Z-IFE target

Reactor References

R. Moir "The logic behind thick, liquid-walled, fusion concepts". LLNL UCRL-JC-115748, 1994.

R. W. Moir, R. H. Bulmer, K. Gulec, P. Fogarty, B. Nelson, M. Ohnishi, M. Resnick, T. D. Rognlien, J. F. Santarius, and D. K. Sze, "Thick Liquid-Walled, Field-Reversed Configuration Magnetic Fusion Power Plant," Fusion Technology, 2, 2, Part 2 (March 2001) 758.

R. W. Moir, R. L. Bieri, X. M. Chen, T. J. Dolan, M. A. Hoffman, et al., "HYLIFE-II: A Molten-Salt Inertial Fusion Energy Power Plant Design-Final Report," Fusion Technology, 25, 1 (January 1994) 5-25.

R. W. Moses, R. A. Krakowski, and R. L. Miller, "Fast-Imploding-Liner Fusion Power," Proceedings of the Third Topical Meeting on The Technology of Controlled Nuclear Fusion, Vol. 1, 109 (May 1978) CONF-780508.

G. E. Rochau, and the Z-Pinch Power Plant Team, "Progress Toward the Development of an IFE Power Plant Using Z-Pinch Technology," Fusion Science and Technology, 47, 3 (April 2005) 641.

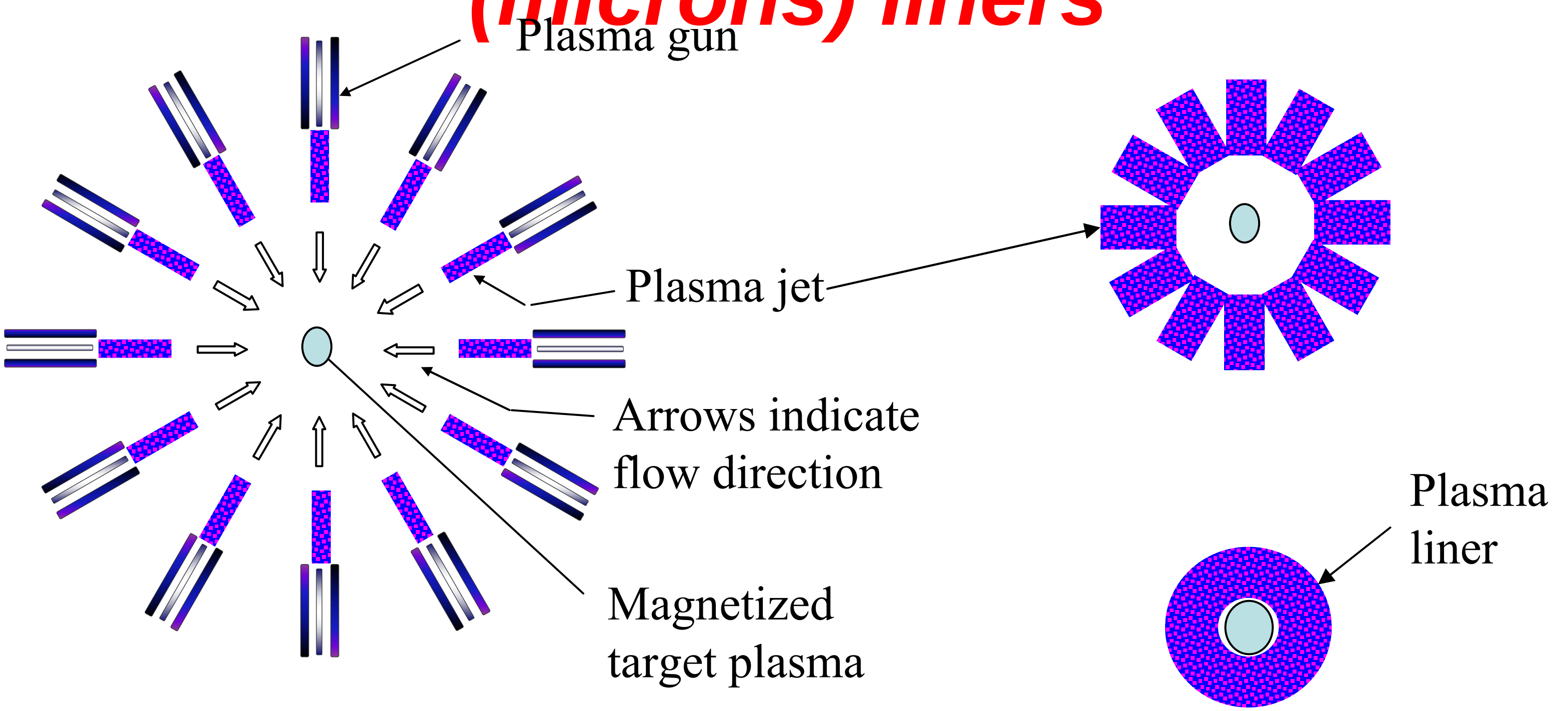
M. J. Schaeffer, "Slow liner fusion", GA-Report GA-A22689, Aug. 1997

P. J. Turchi, A. L. Cooper, R. D. Ford, D. J. Jenkins, and R. L. Burton, "Review of the NRL Liner Implosion Program,'' MegaGauss Physics and Technology, P. J. Turchi, Ed., Plenum Press (1980) 375

Plasma Liner Driven HEDLP and MIF

- Plasma liner provides an avenue for solving three major issues
  - Standoff delivery of imploding momentum
  - Repetitive operation
  - Liner fabrication and cost
- It is capable of faster compression if faster compression is desired
- It can form strongly coupled plasmas
- Remote current drive by lasers or particle beams is possible
- Diagnostics opportunities: Provide clear view of both the liner and the target, thus enhances the diagnostics access

Merging of high Mach number plasma (dusty plasma) jets to form plasma (microns) liners



- An approximately spherical distribution of jets are launched towards a common center
- The jets merge to form a spheroidal shell (liner), imploding towards the center

Supersonic Plasma Jets and Precursor Flows in Wire-Array Z-Pinch

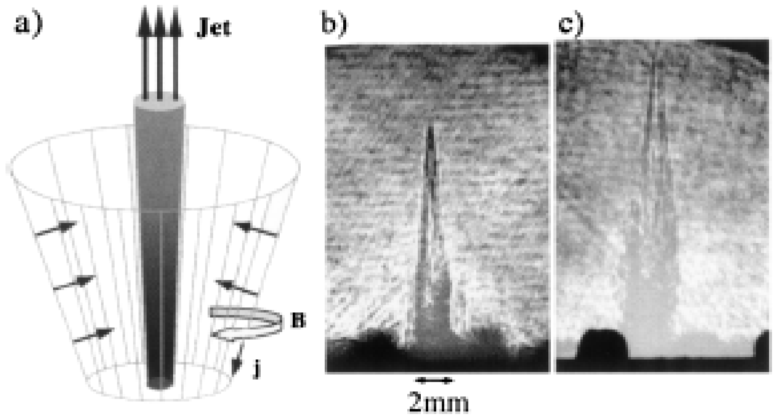


FIG. 1. (a) Diagram of jet formation in conical wire arrays, (b) Laser schlieren image of tungsten plasma jet after launch at 313 ns, and (c) at 343 ns.

J. P. Chittenden, et. al., "Indirect-Drive ICF using Supersonic, Radiatively Cooled, Plasma Slugs," PRL, 88 (23), 2002

Cylindrically converging precursor plasma flow in wire-array Z-pinch Experiments.

S. C. Bott, et. al, Phys Rev E, 74, 2006.

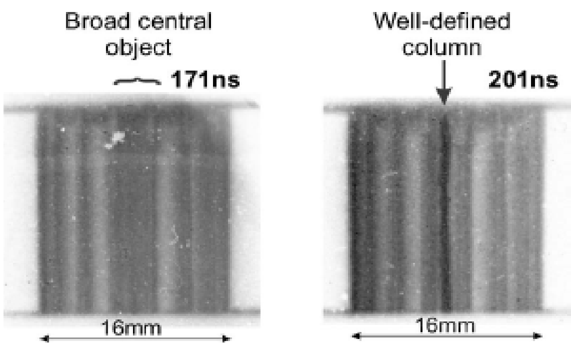


FIG. 2. Side on XUV emission image of a 16 wire tungsten array showing formation of the compact precursor column.

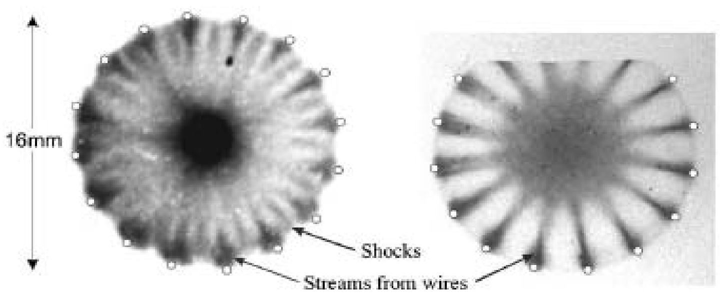
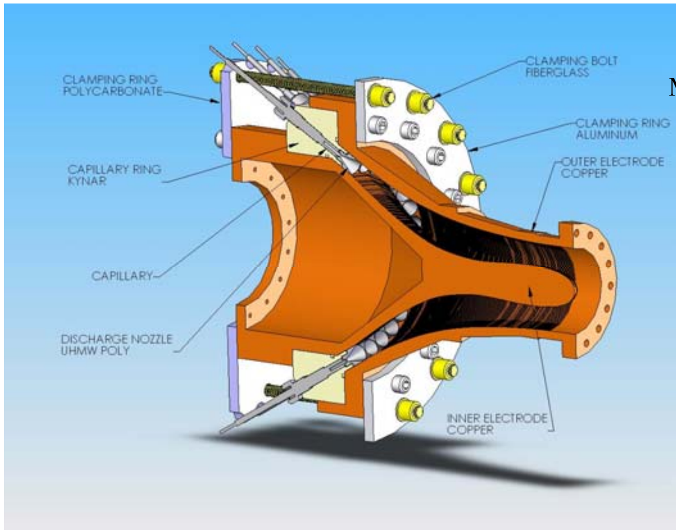


FIG. 3. End-on XUV emission from 16 mm diameter arrays of (left) 16×20 μm Al at 134 ns, and (right) 16×13 μm W at 134 ns. (White circles indicate positions of wires).

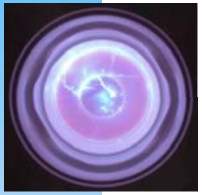
Plasma Jet Research for Fusion Energy Applications

HyperV Technologies Corp. - Chantilly, VA

- **Mission:** Experimental plasma research to develop high momentum-flux-density plasma jets.
  >100 ug >200 km/s 10^{16}-10^{17}cm^{-3} >Mach 10
- **Applications:** Disruption mitigation, refueling, driving rotations, high energy density physics, magneto-inertial fusion.
- **Approach:** Highly collisional armature, preformed plasma with high speed injection from electrothermal plasma discharges.



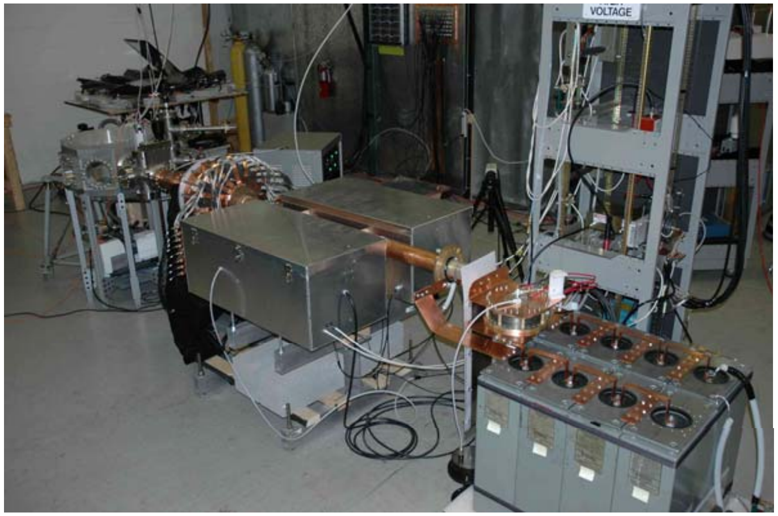
Main Current Pulse



Capillaries Only

Recent Accomplishments

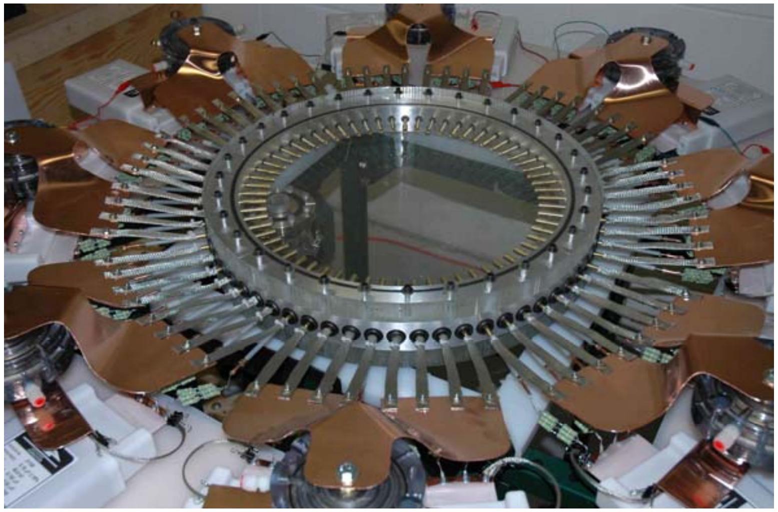
- 100 km/s Prototype Accelerator now operational using 32 capillary injector discharges. Massflow > 100 ug at 70 km/sec
- High resolution spectrometry and high speed imaging fully operational.
- Mach2 modeling identified two electrode profiles which suppress blow-by instability. 32 processor cluster now operational and running Mach2 and LSP.
- 64 plasma injector planar array upgraded to full energy, with injector and jet merging studies underway.
- Facility upgraded with screen room, turbopumped central vacuum chamber, HV switch for main pfn allowing adjustable delays up to 7 us, 68 channels high speed data acquisition.



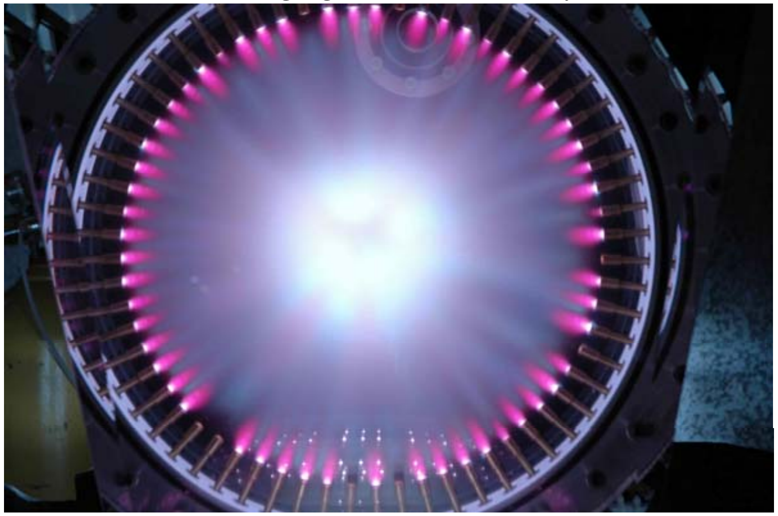
Plasma Jet Plans for FY09

- Develop highly collisional preformed plasma armature with high speed symmetric injection from low jitter plasma injectors.
- Pure hydrogen/deuterium injection with nonablative insulator liners.
- Couple high density, high velocity plasma injector to coaxial accelerator with tailored electrode geometry to suppress blow-by instability.
- Study transport of 200 km/s plasma jets with and without B field.
- Comparison of Mach2 and LSP jet modeling with diagnostic measurements.
- Extensive diagnostic measurements including high resolution spectroscopy, laser interferometry, fast framing camera, Bdot probes, Langmuir probes, photodiode arrays, HV probes and rogowski coils.

Plasma Injector Test Facility



Jet Merging Studies Underway



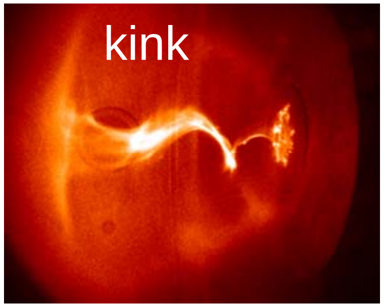
Caltech
Related plasma jet physics:
"Determining how plasma self-organization works"
PI: Paul Bellan

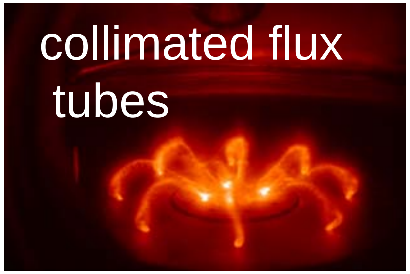
Main results to date

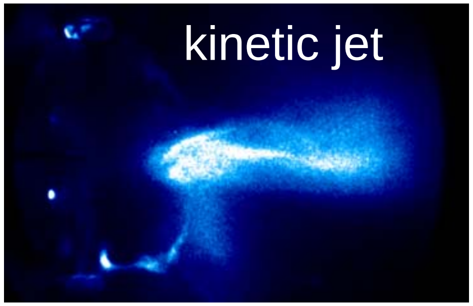
1. <u>**Kink instability fundamental to spheromak formation**</u>
   - kink converts toroidal flux to poloidal flux
     Phys. Rev. Letters 90, 215002 (2003)

2. <u>**High-speed plasma jets fill and collimate flux tubes**</u>
   - **J**x**B** force drive jets which *ingest* plasma from *wall*
   - magnetic flux convected with inflow
   - flow stagnation gives jet collimation and high, localized density
   - **Phys. Rev. Letters 95, 045002 (2005)**

3. <u>**Unstable ion orbits and kinetic jets**</u>
   - effective radial potential a *hill* instead of a valley for fast counter-current ions
   - fast counter-current ions are *ejected* from a flux tube
   - ejected ions form a 'kinetic jet'
   - to appear in **Phys. Rev. Letters 2007**

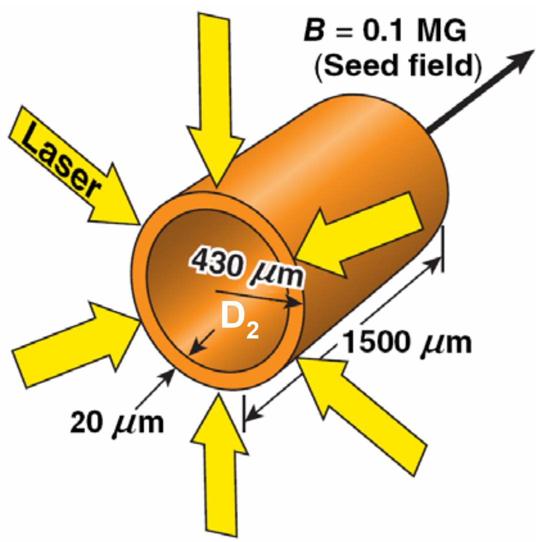




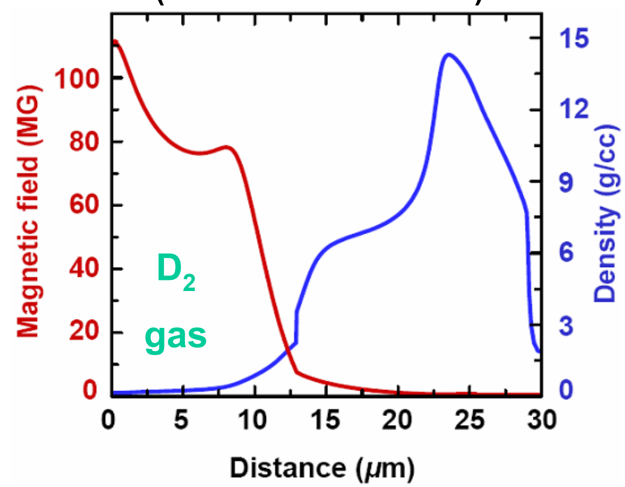


4/25/2007

Magneto-inertial fusion experiments on the OMEGA laser will create MG fields for ICF hot spot insulation



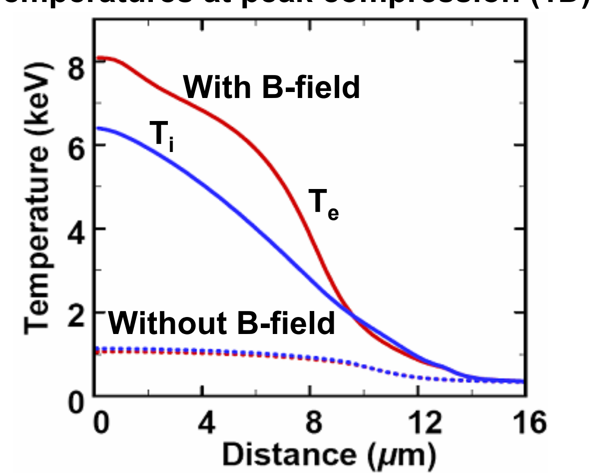
B-field at peak compression
(1D MHD simulations)



A cylindrical target filled with D_2 gas is imploded by OMEGA to compress a pre-seeded ~0.1 MG magnetic field to high values.

The compressed magnetic field inhibits the thermal transport, leading to increase of the hot spot temperature.

Temperatures at peak compression (1D)



Summary

- Magnetized plasma pervade the physical universe. Some of these plasmas occur at extreme HEDP conditions, including white dwarf stars and magnetars, or with magnetic reconnection, etc.
- Magnetized HEDLP conditions can be achieved by a variety of approaches, embodied by MIF/MTF systems.
- Beyond just enabling fusion (a grand challenge in itself), MHEDLP is a scientifically rich set of parameter space.
- At the moment, it pushes our technologies to the limits, in order to create the multi-keV, dense, ultra-high field plasmas.
- It will provide laboratory tests of our computational/simulation capabilities, which can be applied to other situations, including astrophysical objects.